

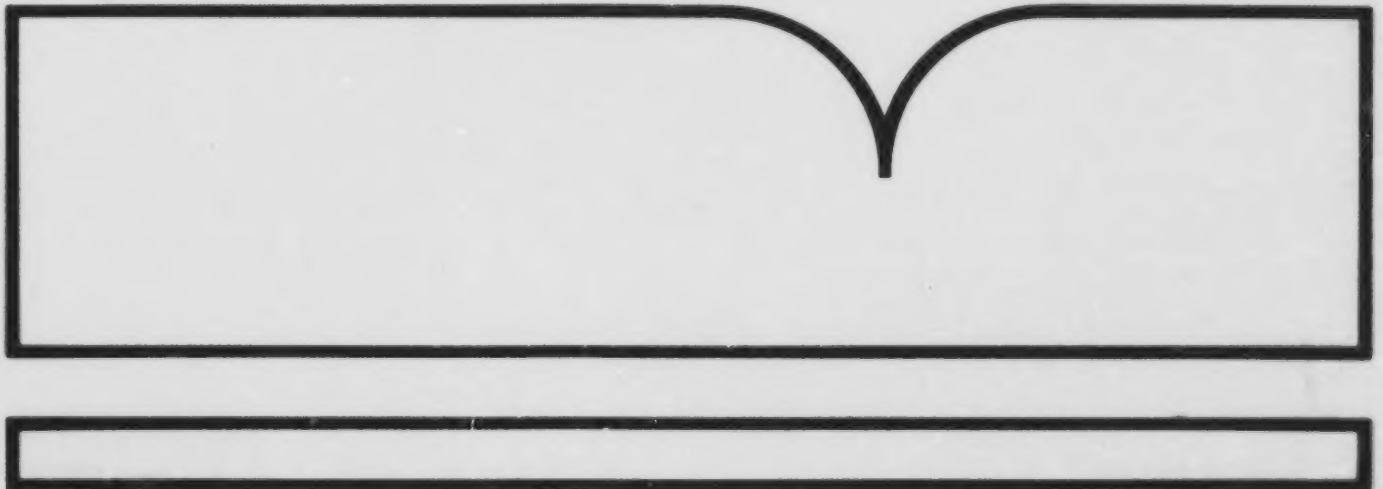
Evaluation of Low Emission Coal Burner
Technology on Industrial Boilers
Third Annual Report (1981)

Energy and Environmental Research Corp.
Irvine, CA

Prepared for

Industrial Environmental Research Lab.
Research Triangle Park, NC

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EVALUATION OF LOW EMISSION COAL BURNER
TECHNOLOGY ON INDUSTRIAL BOILERS
Third Annual Report (1981)

by

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Combustion	Distributed Mixing Bur- ners	21B
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ABSTRACT

This report summarizes the third year's effort on the Evaluation of Low Emission Coal Burner Technology on Industrial Boilers. The objective of the program is to conduct a field evaluation of the Distributed Mixing Burner (DMB) on an industrial size boiler. The DMB concept provides for controlled mixing of the coal with the combustion air to minimize NO_x emissions while maintaining an overall oxidizing environment in the furnace to minimize slagging and corrosion. The major accomplishments this year included completion of baseline host boiler tests, completion of prototype DMB tests in a burner test facility and installation of the DMBs in the host boiler.

This report is submitted under Contract No. 68-02-3127 by Energy and Environmental Research Corporation and Foster Wheeler Development Corporation under the sponsorship of the U.S. Environmental Protection Agency. It covers the period from October 1980 to September 1981.

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1.0 INTRODUCTION AND SUMMARY

For the last several years Energy and Environmental Research Corporation has been working with the EPA to develop a low NO_x pulverized coal burner. This "Distributed Mixing Burner" (DMB) provides for controlled mixing of the coal with combustion air to minimize NO_x emissions while maintaining and overall oxidizing environment in the furnace to minimize slagging, fouling and corrosion. DMBs have been tested at firing rates of up to about 29.3 MW (100×10^6 Btu/hr) in single and four-burner arrays in two research furnaces. The tests covered wide ranges of burner adjustments and operating conditions. When fired in the research furnaces under optimum conditions, NO_x levels less than 65 ng/J ($0.15 \text{ lb}/10^6 \text{ Btu}$) were obtained. However, the DMB performance has not been evaluated in a commercially operated steam generator. The objective of this program (EPA Contract No. 68-02-3127) is to evaluate the DMB concept on a commercially operated industrial size boiler. The goal is to attain NO_x emission levels less than 87 ng/J ($0.2 \text{ lb}/10^6 \text{ Btu}$) for new boilers without adverse effects on boiler operability and durability, thermal efficiency and the emissions of other pollutants. The field evaluation involves: 1) translation of the development burner test data into practical prototype DMBs; 2) verification of the prototype burner performance through testing in a research furnace; 3) construction and installation of these burners in the field boiler and evaluation of performance under typical operating conditions; 4) documentation of the results; and 5) input to the parallel utility field evaluation (EPA Contract No. 68-02-3130).

To accomplish the program objectives, the efforts are organized into the following nine tasks:

1. Program Definition
2. Prototype Construction and Testing
3. Boiler Characterization
4. Burner Installation
5. Performance Evaluation
6. Industry Coordination
7. Boiler Restoration
8. Data Analysis
9. Design Approach Documentation

Figure 1-1 shows how these tasks interact to achieve the program objectives. In Task 1, all of the basic elements of the program are planned including boiler selection, burner design and establishment of a measurements plan. A host site boiler is selected and negotiations with the operator completed so that a firm schedule for the remaining aspects of the study can be established. The final burner design is established once the boiler has been selected. Based on the final burner design established in Task 1, a prototype burner including all controls is then constructed, installed in the Large Watertube Simulator Furnace (LWS) and evaluated using several coals as part of Task 2. In addition, during Task 2 the commercial burner used in the host site boiler is also evaluated in the LWS so that a one-to-one comparison of operating characteristics is determined and any potential problems are identified. At the conclusion of Task 2, the burner and burner systems are ready for fabrication and installation in the host boiler.

While Task 2 is being accomplished, the Task 3 - Boiler Baseline Evaluation of the host unit is initiated. This effort establishes the normal operating characteristics as well as the potential for reducing NO_x emissions by utilizing various combustion modification techniques associated with operating point changes. Following the baseline characterization, the low NO_x coal burners and all support systems are installed in the host boiler in Task 4. The burners and burner systems then undergo checkout testing to ensure that they are able to perform in a manner similar to the original burners. Any necessary changes in the burner design required for operational flexibility are then accomplished, checked out in the prototype LWS unit and incorporated and verified in the host boiler before proceeding to Task 5 - Performance Evaluation.

Following Task 4, the low emission burner system is ready for extensive evaluation. The retrofit boiler is then operated over a sufficient range of conditions consistent with the steam requirements to define the multi-burner optimization of emissions so that the operating point can be established. Once this is defined then long term evaluations (18 months) are conducted with the boiler operating under a "normal duty cycle".

At the conclusion of this task, the boiler/burner system is inspected and the condition of all systems documented. After the conclusion of Task 5, Task 7 involves the restoration of the boiler.

The remaining Tasks 6 and 8 are accomplished concurrent with all of the other tasks. Lastly, the Final Report, Task 9, involves integration of the overall effort into an evaluation of this technology's applicability to coal-fired industrial boilers.

Originally the program involved field evaluation of DMBs on two industrial size boilers. Work on the initial field evaluation has been in progress for three years. The boiler is Pearl Station, a 98,000 kg/hr (215,000 lb/hr) unit owned and operated by Western Illinois Power Corporation (WIPCO). DMBs have been installed in the WIPCO unit and testing will begin in 1982. Due to the complexity of the burner installation at WIPCO and the resultant high cost, only one field installation will be completed. Work on the second field evaluation will proceed only through prototype burner testing in the LWS.

Progress on the nine program tasks is summarized in Table 1-1. Key accomplishments this year include the following:

- Completion of the prototype burner tests for the WIPCO unit (Task 2)
- Completion of the baseline field test of the WIPCO unit (Task 3)
- Installation of the DMBs at WIPCO (Task 4)

Several versions of the prototype burner for the WIPCO unit were tested in two research furnaces, the LWS and the Medium Tunnel (MT) in Task 2. The initial prototype burner was designed by integrating the DMB design criteria developed under EPA Contracts 68-02-1488 and 68-02-2667, requirements of the WIPCO unit and Foster Wheeler burner components. This burner was tested in the LWS to optimize performance and to verify that the performance was compatible with the host boiler requirements. Only a brief series of tests was conducted before the LWS, which was approaching its design life, failed. The LWS furnace was then rebuilt to somewhat different specifications and the prototype burner tests were resumed. These tests indicated that low NO_x emission could be achieved but flame stability at the design operating point was unsatisfactory. At this point the burner design parameters could have been itera-

TABLE 1-1. PROGRAM STATUS SUMMARY

Task	Program	Field Evaluation	Second Prototype Burner Evaluation
Task 1 - Program Definition Host Boiler Selection Burner Engineering Design Analytical Measurements Plan	Boiler inventory evaluated Design criteria identified Measurements protocol completed	Selected Prototype DMB designed Sampling system constructed and installed	Selected
Task 2 - Prototype Construction and Testing Prototype Burner Tests Host Burner Tests		Completed Completed Completed Completed Scheduled for 1982	Scheduled for 1982
Task 3 - Boiler Baseline Evaluation Task 4 - Burner Installation Task 5 - Performance Evaluation Task 6 - Industry Coordination Task 7 - Restoration Task 8 - Data Analysis Task 9 - Guideline Manual	Two Panel Meetings were held	April, 1984 In progress September, 1984	

tively optimized to achieve the desired performance. However, this would have resulted in a considerable delay in the field evaluation. Consequently, a decision was made to modify the burner by incorporating proprietary Foster Wheeler design parameters into the burner exit. Since burners with this exit geometry were known to have adequate flame stability based on commercial experience, preparations for installation of the DMBs at WIPCO were initiated while confirmation tests of the prototype burner in the LWS were completed. The LWS tests indicated that the DMB operation was compatible with the WIPCO unit requirements and that flame stability was acceptable at the design point. NO_x emissions were in the same range as the initial prototype DMB. The final version was also tested in another research furnace, the Medium Tunnel (MT), to evaluate the effects of furnace confinement on performance. Section 2 of this Annual Report summarizes the tests of the initial prototype DMB (which were documented in the Second Annual Report) and discusses the tests of the final version of the prototype burner. Data are presented suggesting that NO_x emissions from the DMBs installed in the WIPCO unit will be in the range of 87-130 ng/J (0.2 to 0.3 lb/10⁶ Btu).

The Task 3 baseline field tests at WIPCO were conducted in the following four test series:

1. Burner Modification Tests - Summer, 1980. These tests included evaluation of burner and boiler performance over wide ranges of operating parameters including load, excess air and burner settings. The results of these tests were summarized in the Second Annual Report and are discussed in more detail in Section 3 of this report.
2. 30 Day Test - Summer, 1980. Following the burner modification tests, burner and boiler performance were monitored for the 30 days while the operation followed the normal duty cycle. The test results are discussed in Section 3 of this report.
3. Effluent Stream Analysis - Spring 1981. An EPA Level 1 environmental assessment was conducted at one full load operating condition. Data from this test are being evaluated and will be discussed in the next Annual Report.

4. Thermal Efficiency Test - Spring, 1981. Boiler efficiency and heat absorption distribution were measured at one full load operating condition. Data from this test are being analyzed and will be discussed in the next Annual Report.

Based on the results of the prototype burner tests in the LWS, field operable DMBs were constructed and installed in the WIPCO unit in Task 4. The central portions of the DMBs were similar to the final prototype burner but due to practical constraints, the tertiary air ports and flow measurement/control system were different. Full scale models of the flow measurement/control components were calibrated in a flow facility at EER. The field installation of the DMBs and flow system calibrations are discussed in Section 4.

The DMBs are now operating with the tertiary air ports closed. Plans for NO_x and performance optimization tests with the tertiary air ports open are discussed in Section 5. Plans for the development of an alternate DMB based on the EPA designed parameters are also presented. The Appendix is a description of the Medium Tunnel test facility.

2.0 PROTOTYPE BURNER TESTS

The development and testing of the prototype DMB for the WIPCO field evaluation has been completed. The objectives were to:

- Integrate the DMB design criteria and commercial burner components into a burner design meeting the requirements of the host boiler.
- Optimize the burner performance through iterative testing in a research furnace.
- Verify that all aspects of burner performance meet the host boiler requirements and that the burner is fully compatible with host boiler systems.

It is well known that burner performance is influenced by furnace environment. Since the basis of the DMB development was testing in a research furnace rather than a field operating boiler, some assurance is required that the research furnace test results are meaningful and can be related to field performance. The approach was to "calibrate" the research furnace against field performance by testing a commercial burner in the field as well as the research furnace. A field evaluation of the original equipment Foster Wheeler Intervane Burner was conducted at WIPCO and the results are discussed in Section 3. A similar Intervane burner was tested in the LWS. The test results were discussed in the First Annual Report. Comparison of the field and LWS test results indicated similar performance especially in the key areas of flame shape and stability. However, NO_x emissions were lower and CO and smoke emissions were higher in the LWS than in the field operating boiler. This was attributed to the design of the LWS which had a significantly lower heat release/cooled surface area than the WIPCO furnace.

The initial prototype burner design was based on the DMB design criteria developed under EPA Contracts 68-02-1488 and 68-02-2667. It should be noted that these criteria resulted in optimum performance in a burner with a central coal nozzle with impeller/spreader and a long refractory exit. The prototype burner utilized a Foster Wheeler annular coal nozzle with tangential inlet and a much shorter refractory exit (required by host boiler windbox depth limitations). Consequently, it was expected that some adjustment of design parameters would be required to optimize performance.

Prototype burner tests in the LWS were initiated in December, 1979. These tests utilized the Utah bituminous coal which was used as a baseline fuel in previous burner tests. Later testing used the host boiler coal. The tests were directed toward evaluation of burner performance under unstaged conditions (with the tertiary air ports closed). Some testing was also conducted under staged conditions. However, the testing was halted when the LWS furnace walls (which had already exceeded their design life) deteriorated. Analysis of these data showed that the operability, flame shape, smoke and CO emissions for the prototype DMB were comparable to the Foster Wheeler Intervane Burner as installed at the host site; however, NO_x emissions were much lower (as expected).

The LWS was rebuilt with several design changes to make burner performance in the LWS more representative of burner performance in field units as well as to facilitate testing. The original LWS was cooled on all surfaces, resulting in a thermal environment significantly cooler than that typically found in field operating boilers, such as the Western Illinois Power Cooperative (WIPCO) host boiler. To produce a thermal environment comparable to that found in the WIPCO furnace, the new LWS was partially lined with insulating refractory. The other major change was the installation of an exhaust duct on the outlet of the LWS. The combustion products in the previous design were vented into the atmosphere from the top of the LWS. Because of the diffuse nature of the exhaust, the combustion products were sampled at the furnace outlet, or nose, with the multiple probes. With the installation of an exhaust duct in the rebuilt LWS, more representative samples of the process can be obtained in the well-defined flow of a circular duct.

The prototype burner was retested in the new LWS under both unstaged and staged conditions. The NO_x emissions from these tests were nearly identical to the results obtained in the old LWS. However, the CO emissions were substantially lower and in the range of CO emissions from the baseline field test at WIPCO. These results suggest that the NO_x emissions from the DMB are insensitive to furnace thermal environment over the range investigated. Thus, the NO_x emissions from the DMBs operated in the field are expected to be in the same range as the test results in the LWS if comparable operating conditions can be achieved. The results of these tests were discussed in the Second Annual Report.

During the third year (ending November, 1981) the prototype burner tests in the new LWS were continued to identify optimum operating conditions. These tests confirmed the earlier test results, but showed that operation at the burner design point resulted in flame instability. As the combustion air was diverted from the burner throat to the tertiary air ports, the flame became unstable at a burner zone stoichiometry of 85 percent theoretical air while the design point was 70 percent theoretical air.* Stability limits were observed with some of the development DMBs and performance was improved by adjusting nozzle and exit geometry.

Based on the original program plan, the next step would have been to modify the prototype burner geometry, retest in the LWS and thus iteratively search for the conditions which optimize performance. However, this would have resulted in a delay in the field installation of the DMBs by about one year (due to the outage schedule at WIPCO). The alternative was to incorporate a proven burner configuration known to be stable under staged operating conditions and to confirm burner performance in the LWS while preparations were being made for the field installation. The Foster Wheeler Controlled Flow Burner has been operated in Japan with burner zone stoichiometries comparable to the DMB but using overfire air ports instead of tertiary air ports. Thus it was decided to incorporate the Foster Wheeler geometry into the DMB. This modified prototype DMB was tested in the LWS under unstaged and staged conditions. The unstaged tests verified that flame stability and shape were satisfactory over the WIPCO boiler operating range. Thus the DMBs can be operated unstaged if a problem develops with the tertiary air port system. The staged tests covered a range of operating conditions and burner settings. Flame stability at the burner design point was satisfactory and NO_x emissions were comparable to the original prototype DMB tests. Following the LWS tests, the modified prototype DMB was tested in another research furnace, the Medium Tunnel, to evaluate the effects of furnace design on burner performance.

Based on the successful completion of these tests, burners with the modified design were installed in the WIPCO furnace. The remainder of this sec-

* Burner zone stoichiometry is the ratio of the air supplied through the burner throat to the air required for stoichiometric combustion of the fuel. It is expressed in terms of percent of theoretical air requirements.

tion discusses the tests of the modified prototype burner in the LWS and MT. The following subsection reviews the burner and test facility designs, fuels and test procedures. Subsection 2.2 presents the test results and Subsection 2.3 discusses the implications for operation of the burners at WIPCO.

2.1 Experimental Systems

2.1.1 Prototype Burners

Two prototype burners were tested. The first burner (Prototype 1) was based on the DMB design criteria and was tested in the old and new LWS furnace. The design of the central portion of Prototype 1 is shown in Figure 2-1.

The following Foster Wheeler commercial burner components have been incorporated into the design:

- Annular Coal Nozzle
- Telescoping Coal Nozzle for Primary Velocity Control
- Registers for Swirl Control and Flow Shutoff
- Air Hoods for Secondary Flow Rate Control and Measurement
- Commercial Flame Scanning and Ignition System

The coal and primary air enter the annular coal nozzle through a tangential inlet to provide swirl. The coal nozzle is a tapered annulus. The exit end of the coal nozzle is formed from two concentric cones. The inner cone can be moved axially to vary the exit area, and hence, the primary velocity. The outer portion of the coal nozzle is constructed of removable sections so that the overall length of the coal nozzle may be changed to vary the nozzle setback within the burner throat. There are two concentric secondary air passages supplied from a common windbox. Each is equipped with an adjustable register for swirl control, an axially movable sleeve for flow control and a perforated plate (air hood) for flow rate measurement. Pressure taps on both sides of each perforated plate allow the pressure drop to be measured and correlated with sleeve position and flow rate.

The portion of the burner inside the coal nozzle is termed the core, and is supplied with a small amount of cooling air from the windbox. A retracta-

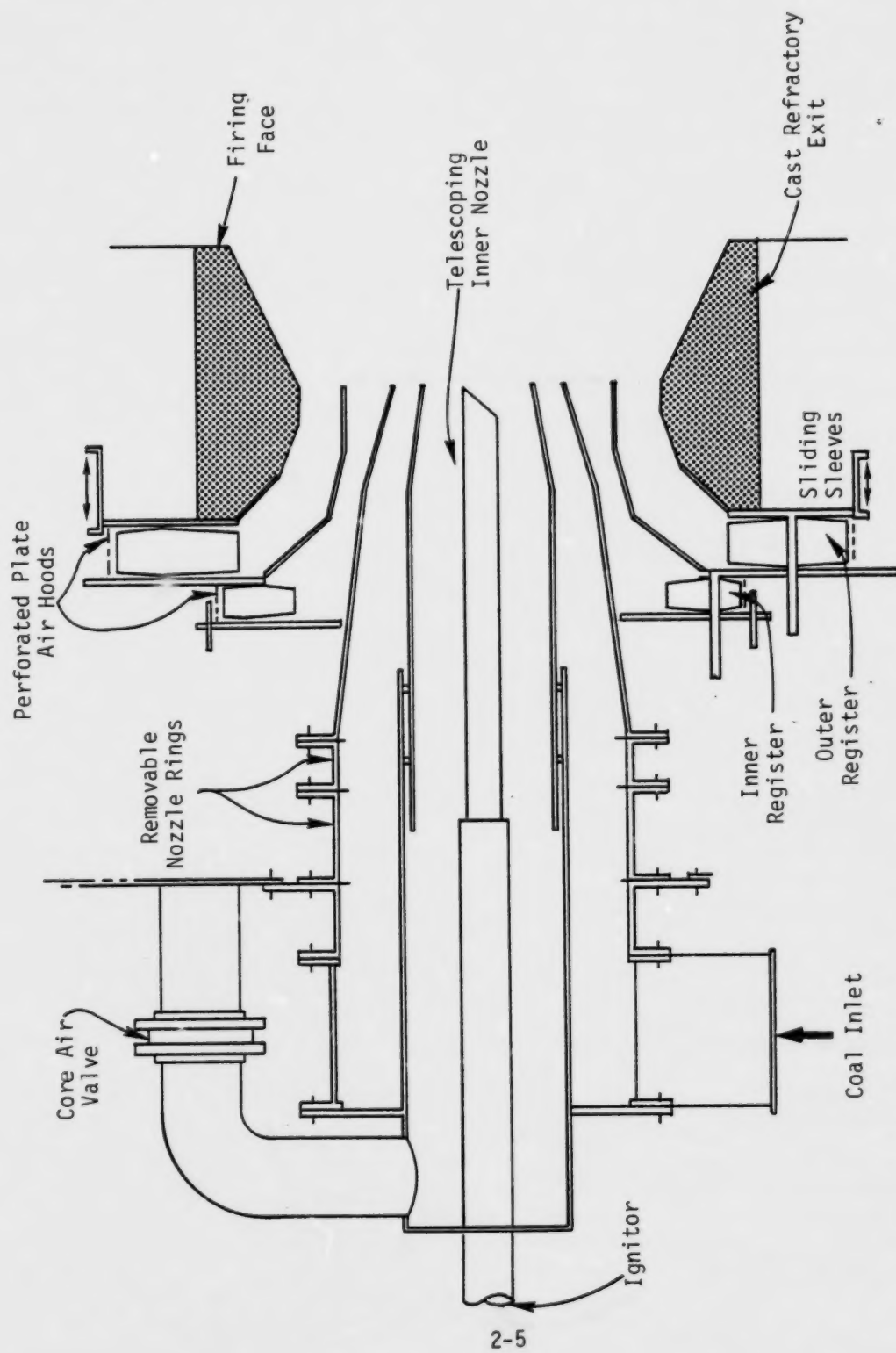


Figure 2-1. Prototype DMB based on Foster Wheeler mechanical components (tertiary ports not shown).

ble ignition system, including spark ignition, an oil gun and an ignition flame scanner are located in the core on the burner centerline. The main flame scanner views the flame through the inner secondary air passage.

Tertiary (staging) air is supplied from the windbox through four air ports spaced uniformly around the burner exit. The port spacing matches the burner spacing at the WIPCO unit.

The burner dimensions and ranges of adjustment are listed in Table 2-1. The development and design of Prototype 1 are discussed in detail in the Second Annual Report.

The second burner (Prototype 2) was designed by modifying the burner geometry to match the geometry of the Foster Wheeler Controlled Flow Burner. This included changes to the nozzle, cast refractory exit and flow divider between the inner and outer secondary air passages. The parallel register arrangement of the initial prototype burner was retained. It should be noted that the Foster Wheeler Controlled Flow Burner has a series register configuration with a single perforated plate and air hood assembly.

2.1.2 Research Furnaces

Three research furnaces were used for these tests: the old LWS, the new LWS, and the MT. The characteristics of these furnaces are compared in Figure 2-2 and Table 2-2. The old LWS was the furnace used for the developmental DMB tests under EPA Contract 68-02-1488 and for the Intervane burner and initial Prototype 1 tests under the program. It was similar in shape to a wall fired industrial boiler with a hopper bottom and exhaust exiting above a nose. The target wall was movable allowing the firing depth to be varied. Exhaust composition was measured with an array of sampling probes near the nose. The entire external surface of the furnace was spray cooled. The design of the old LWS is detailed in "Distributed Mixing Burner (DMB) Engineering Design for Application to Industrial and Utility Boilers", a special report prepared under this program.

During the initial testing of Prototype 1, in the old LWS, the furnace walls deteriorated resulting in air infiltration. Testing was halted when the level of infiltration began to affect the test results. The new LWS was

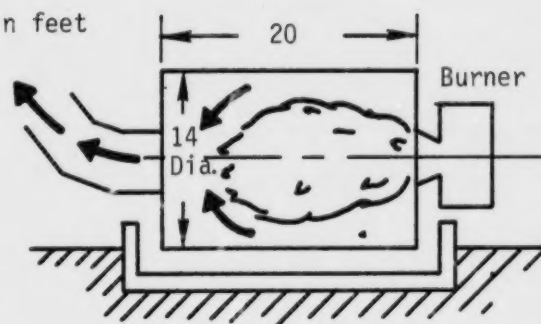
TABLE 2-1. INDUSTRIAL PROTOTYPE BURNER DIMENSIONS AND ADJUSTMENTS

Design Variable	Nominal* Value	Adjustment	
		Range	Method
<u>Fuel Injector</u>			
Core Diameter (in)	9.75		
Core Area (in ²)	74.7		
Nozzle Diameter (in)	14.5		
Annulus Thickness (in)	2.375	1.7-3.3	} Telescoping Nozzle Remove/Replace Nozzle Rings
Primary Area (in ²)	90.5	68-136	
Setback (in)	0	-2 - +2	
<u>Inner Secondary Channel</u>			
Outer Diameter (in)	20.75	Variable	} Replace Secondary Divider
Annulus Thickness (in)	3.125	Variable	
Area (in ²)	173.0	Variable	
Setback (in)	0	Variable	
<u>Outer Secondary Channel</u>			
Outer Diameter (in)	30.25	Variable	} Recast Exit
Annulus Thickness (in)	4.75	Variable	
Area (in ²)	380.5	Variable	
Setback (in)	0	Variable	
<u>Tertiary Ducts</u>			
Distance from Burner C (in)	53	Variable	} Modify Windbox
Spacing around Burner (deg.)	90	Variable	
Number of Ports	4		
Injector Angle (deg.)	0		
Axial Position (in)	0		
Diameter (in)	13.25	Variable	} Sleeve
Total (in ²)	553	Variable	
<u>Throat and Exit</u>			
Throat Diameter (in)	30.25	Variable	} Recast Exit
Throat Area	718.7	Variable	
Half Angle of Exit (deg.)	25	Variable	
Length of Exit (in)	12	Variable	
Length/Diameter	0.40	Variable	

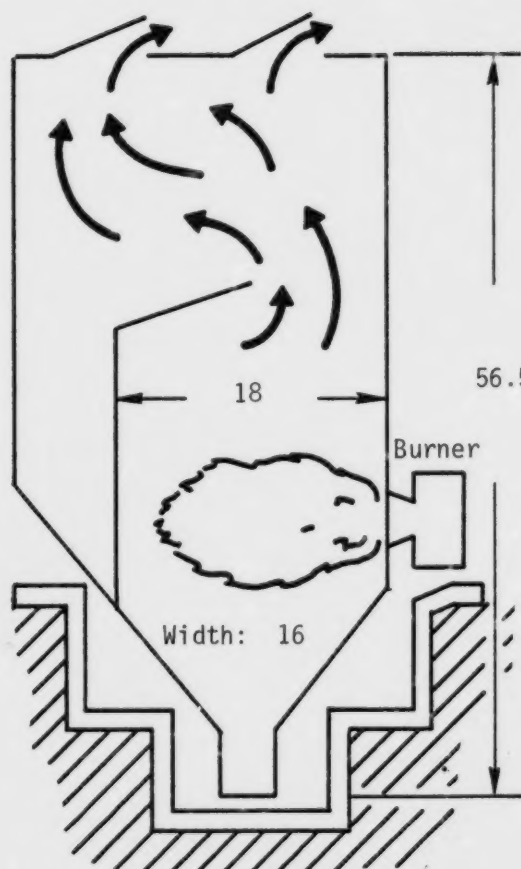
* 1.0 in = 2.54 cm
 1.0 in² = 6.45 cm²

Note:

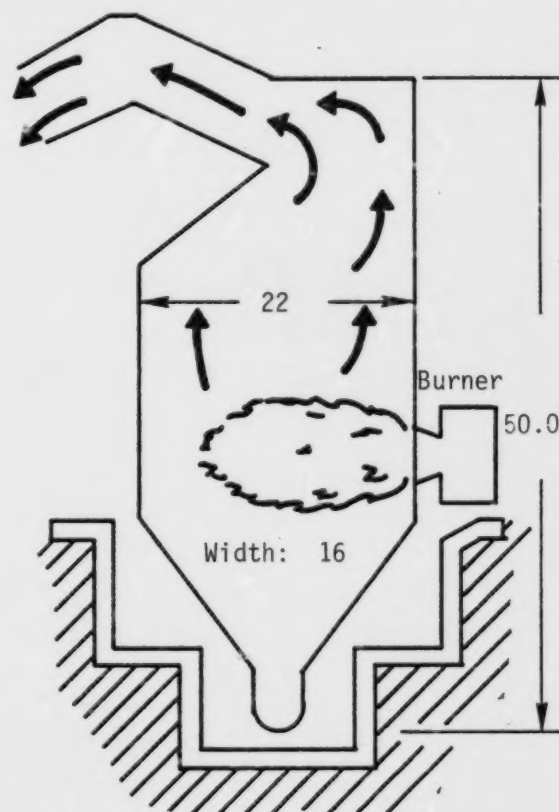
1. All dimensions in feet
2. 10 ft = 3.05 m



Medium Tunnel (MT)



Old LWS



New LWS

Figure 2-2. Comparison of research furnaces.

TABLE 2-2. COMPARISON OF RESEARCH FURNACES

Furnace	Old LWS	New LWS	MT
Shape	Rectangular with Hopper and Nose	Rectangular with Hopper and Nose	Horizontal Cylinder
Firing Configuration	Front Wall	Front Wall	End
Exhaust	Top	Top	End
Firing Capacity (Btu/hr)	125×10^6	150×10^6	80×10^6
Width (ft)	16	16	14 (dia.)
Firing Depth (ft)	18	22	20
Overall Height (ft)	54	50	---
Cooling	External Water Spray	External Water Spray	External Water Spray
Refractory Insulation in Burner Zone	None	Sidewalls (from knuckle up 16 ft)	50 percent of circumference and 10 percent of target wall
Heat Release/Cooled Surface at 70×10^6 Btu/hr Heat Release (Btu/hr-ft ²)*	50,000	100,000	120,000
Burner Tested	Development DMBs Intervane Prototype 1	Prototype 1 Prototype 2	Prototype 2

* see text for definition

NOTE:

1.0 ft = 0.305 m

1.0 Btu/hr = 0.293 W

1.0 Btu/hr-ft² = 3.15 W/m²

built to replace the old LWS. The design is similar to the old LWS with the following exceptions:

- Fixed Geometry. The furnace width and depth are 16 and 22 ft, respectively.
- Furnace Insulation. Refractory insulation was installed on the sidewalls in the burner zone.
- Exhaust Duct. The furnace exhaust was piped through a long straight exhaust duct to facilitate sampling.

The details of the new LWS design were discussed in the Second Annual Report. Following its completion, the new LWS was used to test Prototypes 1 and 2.

To evaluate the effects of furnace confinement and thermal environment, Prototype 2 was also tested in the MT. The MT is a large horizontal tunnel furnace with refractory insulation. The design of the MT is presented in the Appendix of this report.

The heat release per effective cooled surface in the burner zone (Q/A) is an approximate index of furnace heat extraction. Table 2-2 lists this parameter for all three furnaces evaluated at the nominal prototype burner firing capacity 20.5 MW (70×10^6 Btu/hr). For the LWS furnaces, Foster Wheeler's designation of burner zone area was used. This surface is the area of the six-sided box starting at the hopper knuckle and extending 3.05 m (10 ft) above the top row of burners and includes all cooled surfaces in that volume. For the MT, the cooled surface area on the circumference and end walls was used. Comparing the old and new LWS in Table 2-2, the refractory insulation in the new LWS reduces the effective area, which doubles the Q/A . The Q/A for the MT is even higher. The Q/A for the WIPCO furnace is about 4.10×10^5 W/m² ($130,000$ Btu/hr-ft²) which is slightly higher than the new LWS and MT.

2.1.3 Fuels

The WIPCO boiler fires a wide variety of high volatile bituminous coals. At the beginning of this program, coal was being obtained from the Three States Trucking Mine in Huntingburg, Indiana. Consequently, this coal was selected as the design fuel for the prototype burner. At present, WIPCO does not have a long-term coal contract. Small quantities of coal are purchased from several mines based primarily on cost (per unit of heat supplied). Fuels have been obtained from several mines in Missouri and Illinois.

As an illustration of the range of coals fired at WIPCO, Table 2-3 lists the range of compositions measured during the baseline field tests at WIPCO during the summer of 1981.

The prototype burners were tested with three fuels. These compositions are listed in Table 2-4.

- Indiana. This fuel is the prototype burner design fuel obtained from the Three States Trucking Mine in Huntingburg, Indiana. Two shipments of this coal were used at EER. Indiana 1 and 2 are analyses of samples of the first shipment taken over a two-year interval. Indiana 3 is an analysis of a second shipment of this fuel from the same mine.
- Illinois. The Illinois coal is from the Crown II mine in Virden, Illinois.
- Utah. The Utah coal is from the Starpoint 1 and 2 mines in Wattis, Utah. This fuel has been used as a base fuel for the developmental DMBs. The composition listed in Table 2-4 is typical of several shipments received at EER.

2.1.4 Test Procedures

The prototype burners were tested in the research furnaces over a range of loads, excess air and burner settings. The other test variables, including windbox and primary air temperatures, primary stoichiometry and coal fineness, were adjusted to match the conditions at WIPCO. Measurements were made according to the Measurements Protocol as discussed in the Second Annual Report. Table 2-5 lists the standard measurements made at all test conditions and Table 2-6 lists the detailed measurements made at selected test conditions. These measurements are identical to those specified in the standard and detailed formats of the Measurement Protocol with the following exceptions:

1. Particulates. The Measurement Protocol particulate measurements are EPA Method 5 for total mass and cascade impactor for size distribution. While these methods are adequate, it is questionable if the particulate characteristics measured in the exhaust of the research furnace match the particulate characteristics in the field. There are substantial differences in furnace gas velocities and

TABLE 2-3. COAL COMPOSITION FIRED AT WIPCO DURING FIELD TEST

	Based On Samples		
	Range	Average	Standard Deviation
Moisture Content	5.84-17.73	8.35	2.41
Calorific Value (Btu/lb)*			
As Received	9,622-11,710	10,670	758
Dry	11,192-12,691	12,022	526
Ultimate Analysis (% dry)			
Carbon	60.49-72.47	65.92	2.32
Hydrogen	4.23-5.06	4.44	0.69
Nitrogen	1.12-1.53	1.37	0.09
Sulfur	2.73-5.61	3.63	0.66
Ash	9.96-20.90	13.38	2.36
Oxygen (by difference)	5.10-14.23	10.76	2.60

* 1.0 Btu/lb = 2.32 kJ/kg

TABLE 2-4. COALS FIRED IN PROTOTYPE BURNER

	Indiana 1	Indiana 2	Indiana 3	Illinois	Utah
Proximate Analysis (wt %, dry)					
Ash	12.66	11.82	---	11.28	7.87
Volatile Matter	41.01	38.69	---	42.88	44.00
Fixed Carbon	46.33	49.49	---	45.84	48.13
Moisture Content	6.98	5.75	11.03	16.89	7.79
Calorific Value (Btu/lb)*					
As received	11,779	11,527	---	10,480	12,150
Dry	12,663	12,230	---	12,610	13,176
Ultimate Analysis (wt %, dry)					
Carbon	70.06	68.87	71.30	69.61	73.88
Hydrogen	5.00	5.14	4.64	4.92	5.53
Nitrogen	1.66	1.45	1.44	1.24	1.71
Sulfur	3.08	2.56	1.45	3.97	0.77
Ash	12.66	11.82	11.42	11.28	7.87
Oxygen (by difference)	7.54	10.16	9.75	8.98	10.24

* 1.0 Btu/lb = 2.32 kJ/kg

TABLE 2-5. STANDARD MEASUREMENTS FOR PROTOTYPE BURNER TESTS

Test Conditions		Test Outputs	
Parameter	Measurement Method	Parameter	Measurement Method
Furnace Design	Direct Measurement	Flame Characteristics	Direct Observation and/or Color Video
Burner Design		Length	
Burner Adjustments		Width	
Registers		Standoff	
Dampers	Obtain Sample (analyze under detailed format)	Stability	Flame Scanner
Others		Gas Phase Species	Continuous Analyzers
Fuel		O ₂	
Composition		NO/NO _x	
Flow Rate	Weigh belt feeder or calculate from airflow and excess O ₂	CO	
Combustion Air	Venturis	CO ₂	Direct Observation
		Other	
		Smoke	
		Windbox Pressure	
Flow Rate	Thermocouples	Burner Temperatures	Pressure Gauge
Temperature	Venturis or Internal Flowmeters		Thermocouples
Distribution			

TABLE 2-6. DETAILED MEASUREMENTS FOR PROTOTYPE BURNER TESTS

Test Conditions		Test Outputs	
Parameter	Measurement Method	Parameter	Measurement Method
Fuel Composition Size Distribution	ASTM Methods (ultimate and proximate) EER Laboratory Methods (ultimate) ASME Method	Particulate Sample Composition Hydrocarbons SO ₂ N ₂ O	Single Point, Cyclone EER Laboratory Methods (Ultimate) Grab Sample, Gas Chromatography Analysis Continuous Monitor Cryogenic Separation and Gas Chromatograph Analysis

temperature histories which could affect particle settling allowing both total mass and size distribution. Consequently, in the prototype tests, particulate samples were obtained for ultimate analysis only. Samples were withdrawn through a probe in the exhaust duct and separated in a cyclone. The cutoff diameter was 10 microns and based on typical pulverized coal fly ash, 80 to 90 percent of the material was collected. Ultimate analysis of these samples were used to provide an approximate comparison of carbon burnout as burner adjustments were varied.

2. Hydrocarbons. The measurement protocol specifies a flame ionization detector for measurement of hydrocarbons. However, previous tests have shown that hydrocarbon levels are very low. Consequently, during the prototype burner tests, grab samples of hydrocarbon were obtained and analyzed by gas chromatography. The hydrocarbon concentrations were confirmed to be less than 1.0 ppm.
3. Sulfur Trioxide (SO_3). Measurements of SO_3 concentrations were omitted because they are sensitive to the temperature history of the gases. Measurements of SO_3 in the exhaust of the research furnace would not be relatable to measurements from the field operating boilers.
4. Nitrous Oxide (N_2O). Measurements of N_2O were made using a cryogenic separation technique followed by gas chromatograph analysis. This measurement method was developed after the Measurements Protocol was completed.
5. Bottom Ash Sample. Due to the short-term nature of the LWS tests, it was not possible to obtain bottom ash samples which could be related to specific test conditions.

2.2 Prototype 2 Test Results

Prototype 2 was evaluated in the four test series listed in Table 2-7. The test results are discussed in the following four subsections. Subsection 2.2.5 compares the performance of Prototype 1 and Prototype 2.

TABLE 2-7. PROTOTYPE 2 TEST SERIES

Test Series	Staging	Fuel	Furnace
1. Unstaged Performance Verification	Unstaged	Indiana	LWS
2. Staged Performance Optimization	Staged	Indiana	LWS
3. Fuel Effects in LWS	Staged	Utah, Illinois	LWS
4. Furnace Effects	Staged	Utah, Indiana	MT

2.2.1

Unstaged Performance Verification

The initial Prototype 2 tests were conducted in the LWS under unstaged conditions with Indiana coal. The objective was to verify that the burner could operate as a conventional burner with the tertiary air ports closed. This allows the burner to be ignited in the conventional manner and to be adjusted to staged operation for low NO_x emissions. Also, if problems with the tertiary air ports or control system occur, the burner can be operated with the ports closed without need for immediate repairs requiring an outage. The burner was tested over the WIPCO load and excess air range. The flame was stable and could be ignited with the commercial Forney oil-fired ignition system. The flame scanner gave reliable signals for the pilot and main flames. The flame was bright with an overall length of approximately 4.0 m (13 ft). This is considerably shorter than the WIPCO furnace so that no flame impingement problems are expected.

2.2.2

Staged Performance Optimization

Following the Unstaged Performance Tests, Prototype 2 was tested under staged conditions in the LWS with Indiana coal. The objective was to identify the burner settings which gave an optimum balance between flame stability, combustion efficiency and emissions over the host boiler operating range. The criteria used to establish the optimum operating point included the following:

1. Adequate flame stability at the design operating point: burner zone stoichiometry 70 percent theoretical (% T.A.) and overall stoichiometry 120% T.A.
2. Flame stability insensitive to minor burner adjustments.
3. Flame shape compatible with WIPCO furnace.
4. High combustion efficiency as indicated by CO emissions and carbon content of the particulate samples.
5. Low burner pressure drop.
6. Turndown comparable to the Intervane Burner at WIPCO.
7. Low NO_x emissions.

The following burner settings gave optimum results in these LWS tests:

- Inner Nozzle Cone Position = 0.0 cm
- Inner Register = 15° Open
- Outer Register = 15° Open

- Core Air Valve = 45° closed
- Secondary Air Sleeves = 100 percent open

These settings were used for all subsequent tests and will be used as the initial operating point during the field evaluation at WIPCO. Due to the differences between the LWS and the WIPCO furnace, it is expected that some additional adjustments may be required to optimize performance in the field. The nozzle, register and core air valve positions will be adjusted to vary fuel/air mixing and the secondary air sleeves will be adjusted to provide the back pressure required to supply air through the tertiary air ports.

At the optimum burner settings, the flame was stable over a wide range of burner zone stoichiometries from unstaged conditions down to 64 percent theoretical air. As the burner zone stoichiometry was decreased, the flame length increased from 4.0 m (13 ft) for unstaged conditions to about 5.8 m (19 ft) at the design point. These flame lengths are estimates based on direct observation and color video. To confirm the flame length, the composition of the furnace gases was measured near the rear wall. High CO levels and/or low O₂ levels near the rear wall would indicate flame impingement and vice versa. The results are summarized below.

Location	O ₂ (%)	CO @ 0% O ₂ (ppm)
Furnace, 10 cm (4 in) from rear wall	3.4	95
Furnace 46 cm (18 in) from rear wall	3.2	165
Furnace, 76 cm (30 in) from rear wall	3.0	1400
Furnace, nose	5.3	58
Exhaust	4.5	57

These data indicate that an oxidizing environment is present on the rear wall. As the sampling location was moved further into the furnace, the O₂ concentration decreased and the CO concentration increased. The 5.8 m (19 ft) flame length observed visually corresponds to 61 cm (24 in) from the rear

23

wall. This is approximately the location of a considerably increase in the CO concentration.

The NO and CO emissions at full-load are shown in Figure 2-3. These results are similar to those obtained with the development DMBs and Prototype 1. For fixed overall stoichiometry, NO emissions decreased approximately linearly as the burner stoichiometry decreased. Thus it is desirable to operate at the lowest burner zone stoichiometry where flame stability and combustion efficiency are acceptable. As burner zone stoichiometry is decreased, CO emissions remain constant initially and then increase. Further decreases in burner zone stoichiometry result in flame instability with a flame stability limit of about 64% T.A. At the design point (70% T.A.) NO_x emissions are 200 ppm*, which corresponds to 96 ng/J (0.22 lb/10⁶ Btu), and CO emissions are about 70 ppm* which is in the range of typical commercial burners, less than 100 ppm. NO_x emissions are also sensitive to excess air with a slope of about 15 ppm/% T.A. CO emissions and flame characteristics remained constant over the range shown.

Other measurements at the design point are summarized below:

- Particulate carbon content was 4.39 percent indicating a carbon utilization efficiency of 99.15 percent.
- Hydrocarbon emissions were lower than the detectability limit (1.0 ppm) on two tests.
- N₂O emissions were 39 and 42 ppm in two tests.

2-4

Burner performance was evaluated over the load range with fixed burner settings. The CE Raymond bowl mill utilized in the Prototype burner tests required maintaining the primary air flow rate constant for proper coal pulverization. Figure 2-4 illustrates the changes in air flow rates and stoichiometries that occur over the load range with fixed burner settings. The primary stoichiometry increases as load is reduced. This differs from the air flow characteristics of the Foster Wheeler MB mills at the WIPCO boiler. Near full load, the primary air flow rate decreases as load is reduced, but eventually levels off to a constant flow rate for low loads. This difference between the characteristics of the pulverizers should not significantly affect burner performance over the conditions tested. Assuming constant overall stoichiometry, the total air flow rate is proportional to the load. Thus, the windbox air

* All NO_x and CO emissions are reported corrected to 0.0% O₂ and dry conditions.

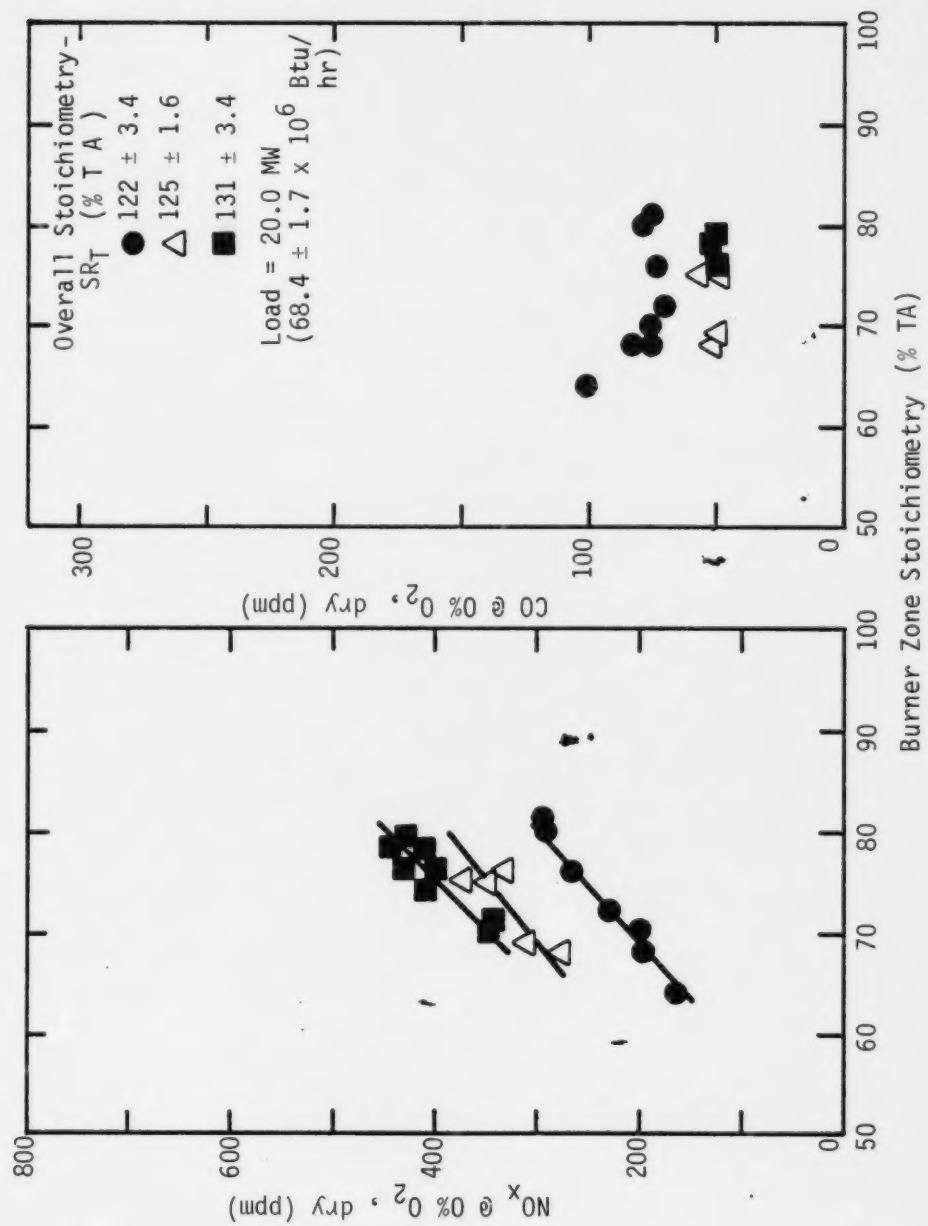


Figure 2-3. Performance of Prototype 2 at optimum configuration in new LWS.

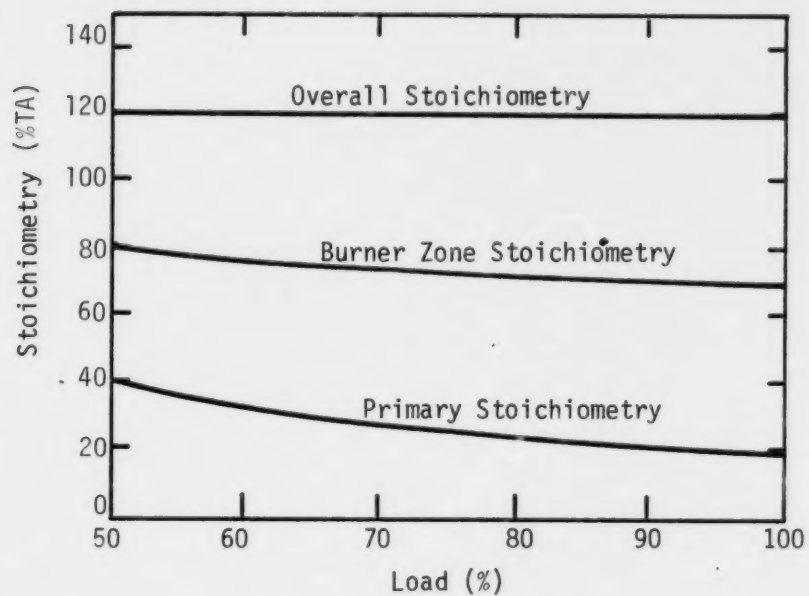
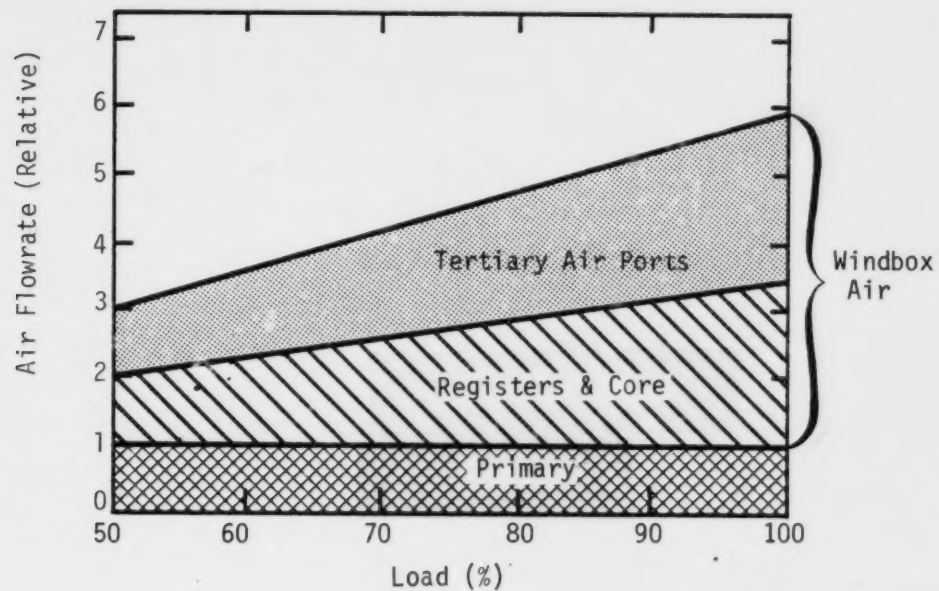


Figure 2-4. Air flowrates and stoichiometries over load range.

flow rate decreases as load is decreased. The distribution of windbox air flow between the registers, core and tertiary air ports depends on burner settings. The net effect is a slight increase in burner zone stoichiometry and a considerable decrease in air flow through the registers as the load is decreased. This can cause flame instability. The solution is to increase the air flow rate through the register by increasing the overall stoichiometry or closing the tertiary air ports. The approach used in the prototype burner tests was to increase overall stoichiometry.

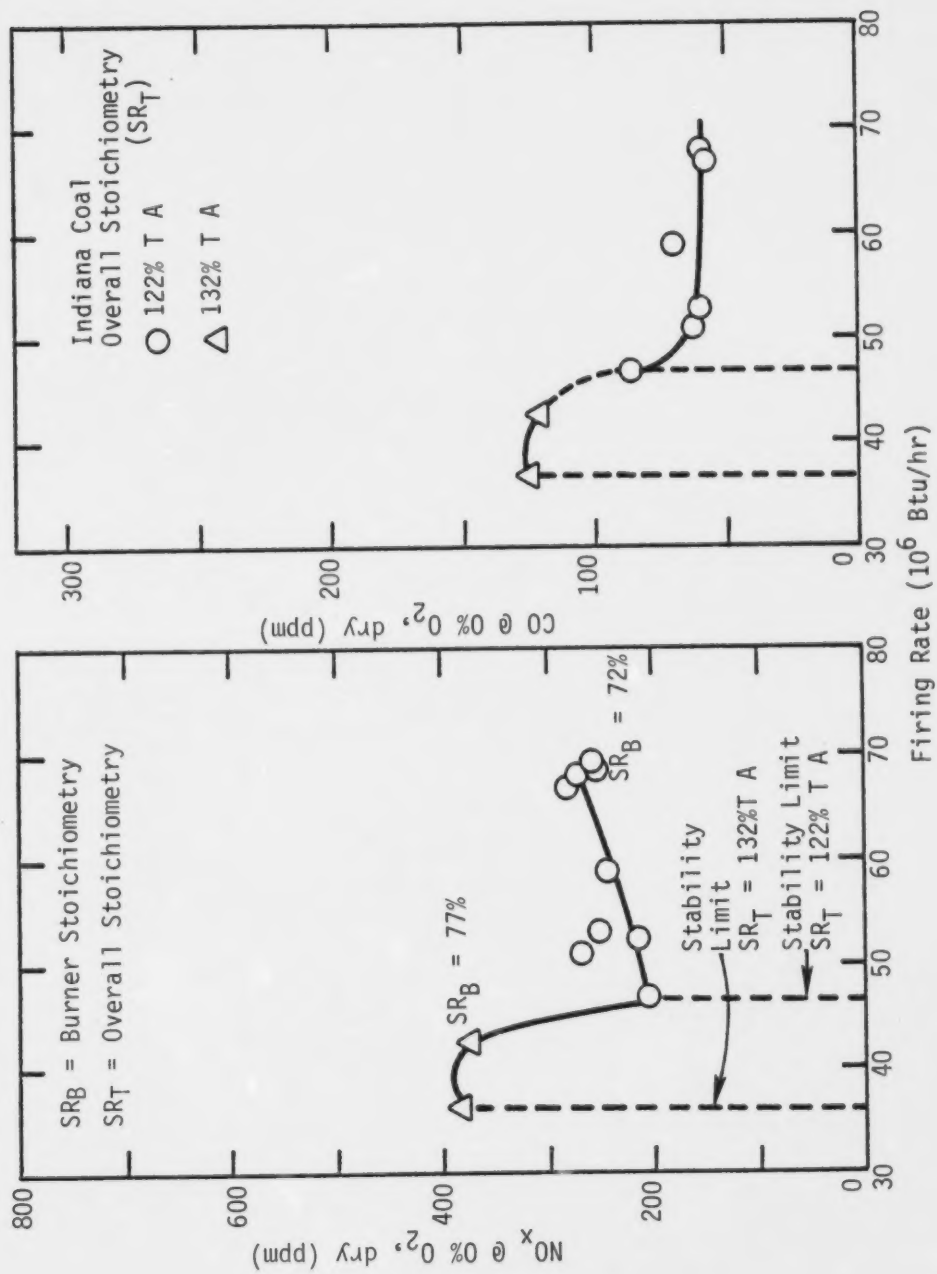
Figure 2-5 shows the performance of Prototype 2 over the load range. At full-load 20.5 MW (70×10^6 Btu/hr), the burner was set-up for an overall stoichiometry of 122% TA and a burner zone stoichiometry of 72% TA. Load was decreased maintaining the overall stoichiometry constant. This resulted in a load of 15.2 MW (52×10^6 Btu/hr). Further decreases in load resulted in a pronounced increase in CO emissions and flame instability. To restore flame stability at lower load, the overall stoichiometry was increased to 132 percent theoretical air. This increased NO_x emissions but allowed stable operation down to 10.8 MW (37×10^6 Btu/hr) which corresponds to a turndown of about 50 percent from full-load.

2.2.3 Fuel Effects in LWS

The preceding tests were conducted with the burner design fuel, Indiana coal. To evaluate the effect of fuel composition, two additional high volatile bituminous coals were tested, Utah and Illinois coals. The compositions of these coals were listed in Table 2-4. The tests were conducted at full load over a range of burner zone stoichiometries. NO_x and CO emissions from all these fuels are compared in Figure 2-6. Flame shape, stability and CO emissions for all the coals were comparable. NO_x emissions from the Utah and Indiana coals were almost identical. However, the NO_x emissions from the Illinois coal were about 100 ppm higher. The reasons for this increase are not clear. The test conditions for all three fuels were similar and the fuel compositions are only slightly different. In comparison to the Indiana and Utah coals, the Illinois coal has higher sulfur, lower nitrogen, lower heating value and lower volatility.

2.2.4 Furnace Effects

Following the LWS tests, Prototype 2 was fired in the MT to evaluate the effects of furnace confinement. In comparison with the LWS, the MT is



NOTE:

1.0 Btu/hr = 0.293 W

Figure 2-5. Prototype 2 in LWS: load range.

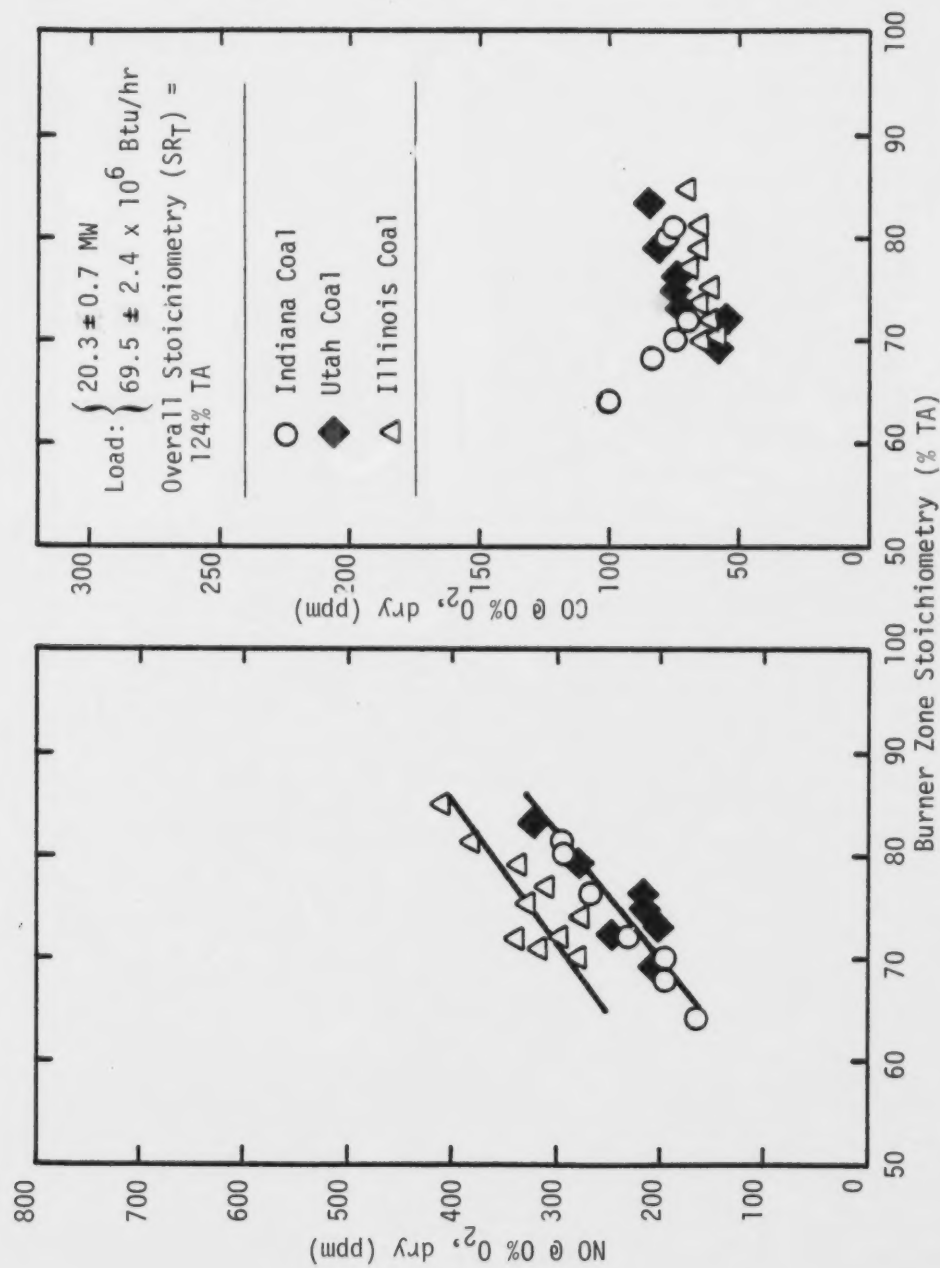


Figure 2-6. Effect of fuel composition on Prototype 2 performance in LWS.

cylindrical as opposed to rectangular and much smaller than the LWS. It also has smaller cooled surface area in the burner zone. These differences were expected to influence the flame characteristics and NO_x emissions. It was planned to fire the burner in the MT at the nominal capacity of 20.5 MW (70×10^6 Btu/hr). However, this firing rate could not be achieved due to the volume of the flame which exceeded the MT furnace volume. Figure 2-7 compares the flame characteristics in the LWS and MT. In the LWS, the flame length was about 5.8 m (19 ft) which is 0.9 m (3 ft) shorter than the furnace depth. In the MT, the flame was constrained by the furnace and extended into the exhaust duct. To avoid overheating of the MT furnace components, the tests were conducted at about 14.6 MW (50×10^6 Btu/hr). At this firing rate in the MT, the heat release per cooled surface area was comparable to full-load firing in the LWS. However, the net heat extraction was greater in the LWS. Furnace exit temperature measurements with an aspirating thermocouple were up to 280°C (500°F) lower in the LWS. Gas temperature measurements at the sampling location in the exhaust duct were about 110°C (200°F) lower in the LWS.

NO_x and CO emissions measured in the LWS and MT with Indiana coal are compared in Figure 2-8. In the MT, NO_x emissions are higher and CO emissions are lower than in the LWS. Figure 2-9 shows similar trends for the Utah coal. It should be noted that the LWS results shown in Figures 2-8 and 2-9 are at higher load than the MT results. Based on the load data in Figure 2-5, the NO_x levels in the LWS at the MT firing rate would be about 40 ppm lower. Thus, comparing the MT and LWS at the same firing rate results in differences somewhat greater than those plotted in Figures 2-8 and 2-9.

The differences between Prototype 2 performance in the LWS and MT may be due to two factors: thermal environment and furnace confinement. The effects of thermal environment on NO_x emissions from Prototype 1 were evaluated by testing in the old and new LWS. The furnace geometries for these furnaces are almost identical. The primary difference is thermal insulation in the new LWS which reduced the cooled surface area by a factor of about two. NO_x emissions from Prototype 1 in the old and new LWS were comparable. This indicates that NO_x emissions were unaffected by thermal environment over the range investigated. Of course, as furnace cooling is reduced further, NO_x emissions would be expected to increase due to thermal NO_x formation.

The smaller size of the MT narrowed and elongated the flame and this may have altered the mixing of the tertiary air. Since the basis of the low NO_x

Note:

1. All dimensions in feet.
2. 1.0 ft = 0.30 m

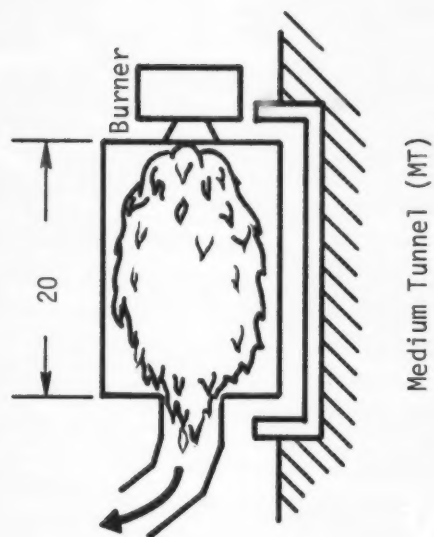
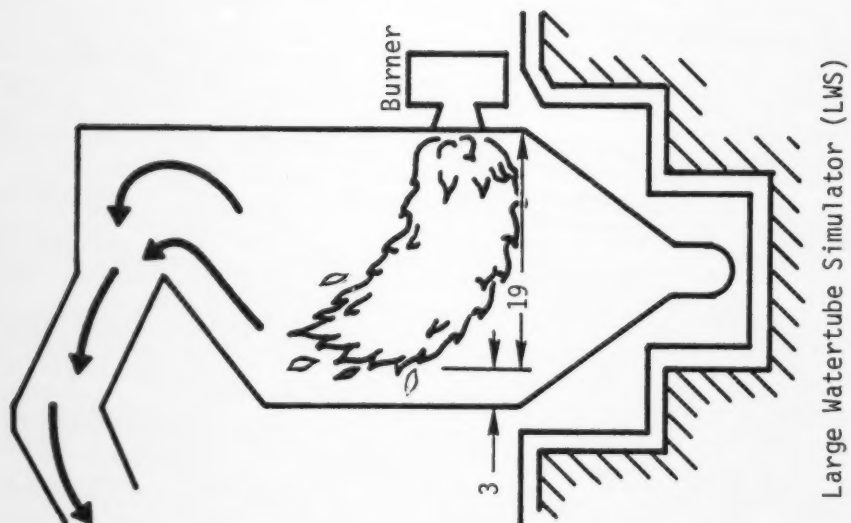


Figure 2-7. Prototype 2 flame containment in the LWS and MT research furnaces.

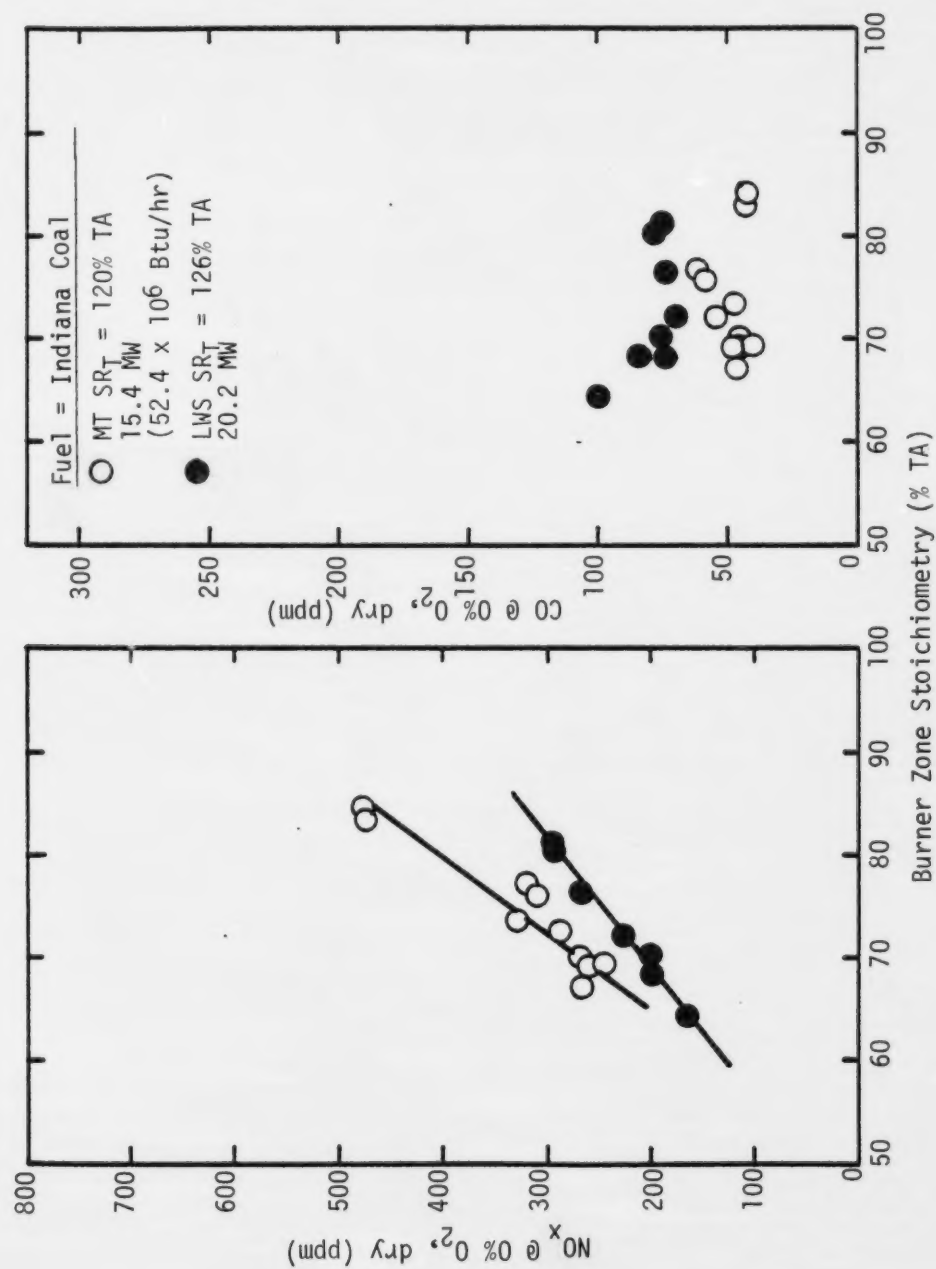


Figure 2-8. Comparison of Prototype 2 performance in the LWS and MT with Indiana coal.

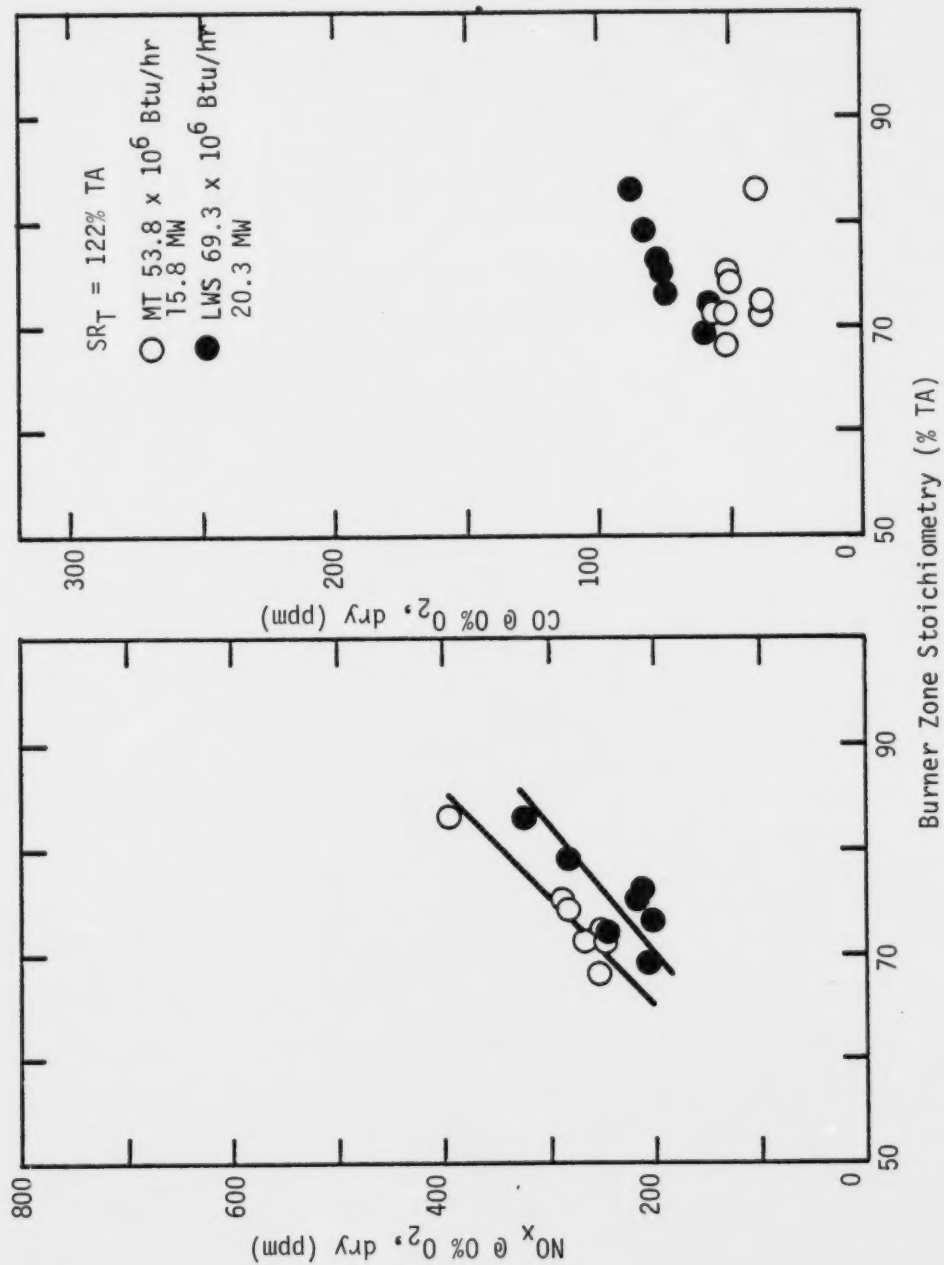


Figure 2-9. Comparison of Prototype 2 performance in the LWS and MT with Utah coal.

emissions of the DMB is delayed mixing of the tertiary air, this may have affected NO_x emissions.

2.2.5 Comparison of Prototype 1 and Prototype 2

The tests of Prototype 1 in the new LWS indicated that a stable flame could be maintained down to a burner zone stoichiometry of 85% TA which is considerably higher than the design point of 70% TA. To improve flame stability, the burner exit geometry was modified to match the design of the Foster Wheeler Controlled Flow Burner. Subsequent tests of the modified burner (Prototype 2) showed that the modification was successful in increasing flame stability. Stable operation was achieved down to a burner zone stoichiometry of 65% TA.

NO_x and CO emissions for Prototype 1 and Prototype 2 in the new LWS firing Ural coal are compared in Figure 2-10. The knee of the CO curve for Prototype 1 occurs at 85 to 90% TA and NO_x emissions at this point are in the range of 175 to 250 ppm. For Prototype 2, the CO emissions are essentially constant down to less than 70% TA where NO_x emissions are about 200 ppm. Thus, Prototype 1 requires less staging to achieve low NO_x emissions than Prototype 2. However, it should be noted that during field operation of Prototype 1 the knee of the CO curve would not be satisfactory due to marginal flame stability and combustion efficiency.

2.3 Application of Prototype Burner Design to WIPCO

One key objective of the prototype burner tests was to verify that all aspects of the burner performance meet the host boiler requirements. Table 2-8 compares the requirements of the WIPCO unit with the performance of Prototype 2 in the LWS. The LWS furnace geometry is similar in shape to the WIPCO furnace. The flame length in the LWS was 5.8 m (19 ft) which is shorter than the WIPCO furnace depth, 6.3 m (20.6 ft). Thus, rear wall flame impingement should not be a problem at WIPCO. The flame was stable over the WIPCO load and excess air ranges and flame stability was not affected by small changes in burner settings or burner zone stoichiometry. The flame scanning and ignition system operation was compatible with commercial standards.

Windbox-to-furnace pressure drop with the secondary sleeves open full was in the range of 3.8 to 5.1 cm (1.5 to 2.0 in.) H_2O . This is less than the 8.9

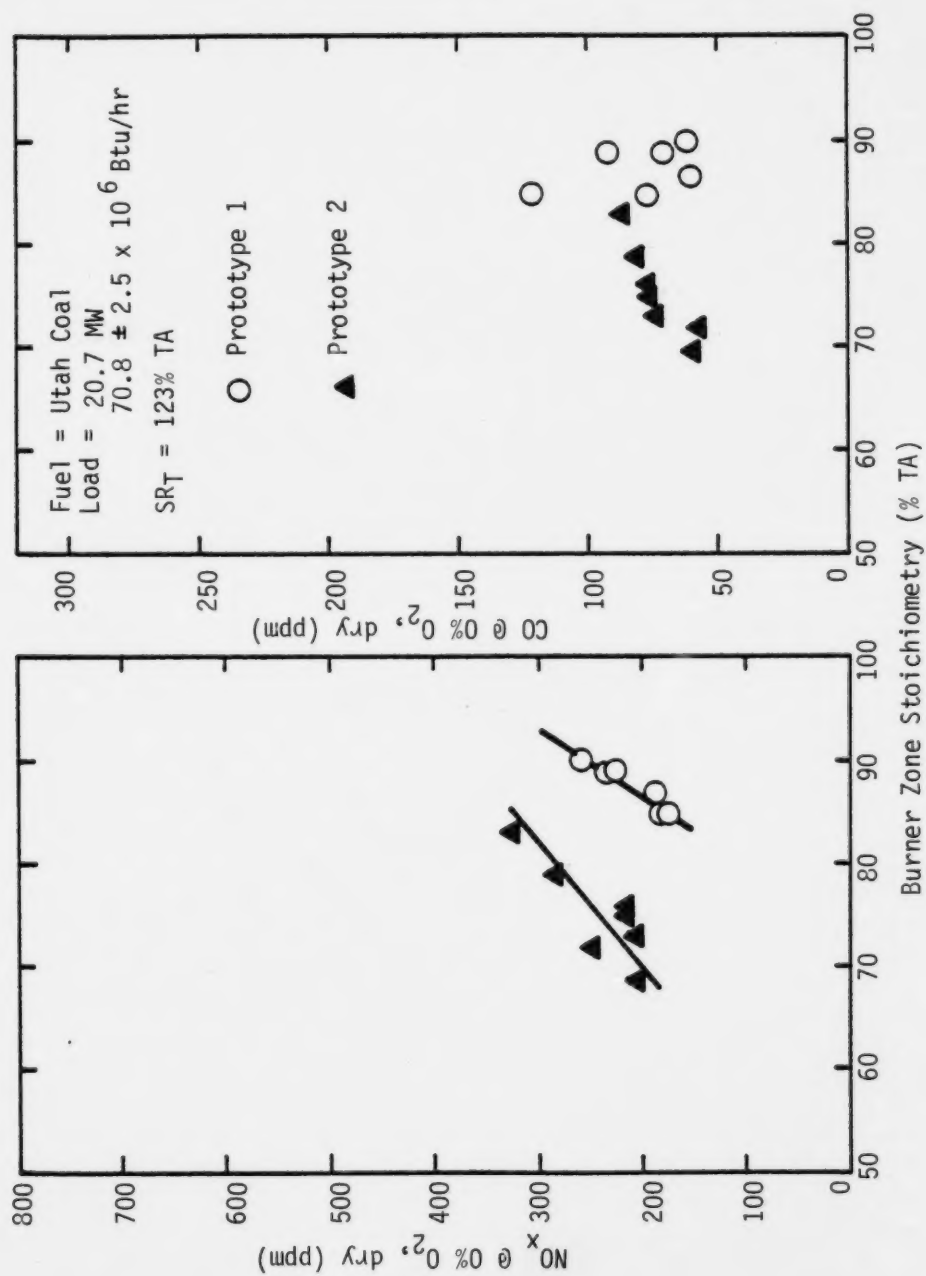


Figure 2-10. Comparison of the prototype burner designs tested.

TABLE 2-8. PROTOTYPE 2 PERFORMANCE SUMMARY

Parameter	Requirement	Demonstrated Performance
Flame Shape	Compatible with host furnace	Flame length: 5.8 m (19 ft)
Flame Stability	Stable over host load range; Insensitive to burner settings	Minimum load less than 50 percent MCR*
Ignition	Compatible with commercial system	Stability insensitive
Flame Scanning	Compatible with commercial system	Confirmed
Pressure Drop	Less/equal to host burner	Confirmed
Efficiency	Equal/better than host burner	3.8 to 5.1 cm (1.5 to 2.5 in) H ₂ O
Tertiary Ports	Locations compatible with host furnace	CO = 70 ppm, Carbon in ash = 4.4 percent
Control System	Compatible with commercial standards	Ports redesigned for Field Evaluation
NO _x	Program goal: 87 mg/J (0.2 lb/10 ⁶ Btu)	95 mg/J (0.22 lb/10 ⁶ Btu) at design point Sensitive to excess air and burner zone stoichiometry Insensitive to load

* Maximum Continuous Rating

cm (3.5 in) pressure drop required by the original equipment Intervane Burner. If required, the secondary sleeves may be closed to increase the pressure drop and to direct more air to the tertiary ports.

CO emissions and carbon content of the particulate were slightly greater than the values measured during the WIPCO baseline test. However, these parameters are sensitive to furnace design and the differences are insignificant.

The prototype burner tests were conducted using a 2 x 2 array of tertiary air ports spaced symmetrically around the burner throat. Due to structural problems, a different array of tertiary air ports will be used at WIPCO. The design and operation of these ports are discussed in Section 4. The WIPCO ports operate with the same air velocity and distribute the air around each burner. Thus the specific design details are not expected to affect burner performance significantly.

NO_x emissions with the design fuel (Indiana coal) were 95 ng/J (0.22 lb/10⁶ Btu) at the optimum full load operating point. This is very close to the program goal of 87 ng/J (0.2 lb/10⁶ Btu). The differences between the prototype burner tests in the LWS and the field operating DMBs at WIPCO are expected to affect NO_x emissions. These differences include the following:

Parameter	Prototype Tests in LWS	WIPCO DMB Field Evaluation
Number of Burners	1	4
Number of Tertiary Air Ports	4	13
Fuel	Indiana	Varies
Furnace Depth (m) [ft]	6.7 [22]	6.3 [20.6]
Thermal Environment, Q/A (Btu/hr-ft ²)	≈100,000	≈130,000

The precise effects of these differences cannot be evaluated based on existing data. Minimum NO_x emissions for the DMBs operating at WIPCO are expected to be in the range of 87 to 130 ng/J (0.2 - 0.3 lb/10⁶ Btu/hr) providing that the operating conditions tested in the research furnaces can be achieved.

3.0 BOILER BASELINE EVALUATION

The objective of the Task 3 - Boiler Baseline Evaluation is to evaluate the performance of the host boiler with the original equipment burners. The data are used to establish the operating requirements for the DMBs and to determine the baseline boiler performance and emissions for assessment of the net change due to retrofitting the DMBs. The specific goals were to evaluate the following:

1. Normal full load operating conditions, performance and emissions.
2. Typical duty cycle and operating ranges as well as operating limits.
3. Effects of operating parameters on emissions.
4. Potential for NO_x reduction with combustion modification but without component changes.

The baseline tests were conducted in the following four test series:

1. Burner Modification Tests
2. 30-Day Baseline Test
3. Effluent Stream Analysis
4. Thermal Efficiency Test

The Burner Modification Tests involved monitoring burner and boiler performance and emissions as the operating conditions and emissions were adjusted over the maximum possible ranges. As part of these tests operating limits were established. Following the Burner Modification Tests the boiler performance and emissions were monitored for 30 days while the operators met the normal duty cycle. The results of the Burner Modification and 30-Day Baseline Tests are discussed in this section.

The Effluent Stream Analysis and Thermal Efficiency Test involved a comprehensive assessment of burner/boiler performance and emissions including an EPA Level 1 Environmental Assessment at the nominal full load operating point. The results of these tests will be presented in a subsequent report.

The measurements conducted during the Burner Modification and 30-Day Baseline Tests followed the Measurements Protocol which was discussed in the

Second Annual Report. Tests at all conditions used a simplified standard measurement format. For selected test conditions, additional measurements were made using a detailed format. These measurements are listed in Table 3-1.

The test results are presented in the following four subsections:

- 3.1 - Normal Full Load Operation
- 3.2 - Operating Range
- 3.3 - Effects of Operating Conditions on Emissions
- 3.4 - Low NO_x Operation

3.1 Normal Full Load Operation

Boiler emissions were measured at the normal full load operating conditions as part of the Burner Modification Test series to establish the baseline emissions. Nominal operating conditions are defined as the following:

1. Load - maximum continuous rating (20 MW_e).
2. Excess Air - design point (18 percent).
3. Other - conditions normally set by operating personnel.

Table 3-2 summarizes the emissions at nominal conditions. The table also shows average emissions during the 30-Day Baseline Test and during the Effluent Stream Analysis for comparison. During the 30-Day Baseline Test, the boiler operating conditions were selected by the operators. During the Effluent Stream Analysis, the boiler was operated at nominal operating conditions. Boiler operating conditions were similar during each of the three test series. The average load measured during the 30-Day Test was 18.5 MW_e showing that the unit primarily operates at or near full load. The excess air was slightly higher during the 30-Day Baseline Test and the Effluent Stream Analysis, but this higher excess air did not significantly affect the boiler emissions. Combustion efficiency as measured by carbon utilization was approximately constant for all three test series.

As shown in Table 3-2, NO_x and CO emissions during the 30-Day Baseline Test and Effluent Stream Analysis were very close to the baseline emissions measured during the Burner Modification Tests. SO_2 , SO_3 , and particulate

TABLE 3-1. SUMMARY OF BASELINE MEASUREMENTS

Standard Format		Detailed Format	
Parameter	Measurement Method	Parameter	Measurement Method
Burner Settings Registers Core Air	Direct Measurement	Fuel Composition	Proximate and Ultimate Analysis by ASTM Methods
Fuel Composition	Ultimate Analysis	Fuel Size Distribution	ASME Method
Fuel Flowrate	Boiler Instrumentation	Flame Characteristics	Video Recorder
Flame Characteristics	Visual Observation	Particulate (fly ash)	EPA Method 5
Gas Phase Species	Continuous Analyzers	Total Mass Size Distribution	Cascade Impactor
NO _x		Composition	Ultimate Analysis
O ₂		Bottom Ash Composition	Ultimate Analysis
CO		Gas Phase Species	Continuous Analyzer
CO ₂		Hydrocarbons	Controlled Condensation
Boiler Operating Data	Control Room Log	SO ₃	Specific Ion Electrode
		NH ₃ , HCN	Continuous Analyzers
		Furnace Wall Gas Composition	
		O ₂	
		CO	
		CO ₂	
		Carbon Distribution	Carbon Balance
		Sulfur Distribution	Sulfur Balance
		Effluent Stream Analysis	EPA Level 1
		Thermal Efficiency	ASME Method

TABLE 3-2. NOMINAL BOILER OPERATING CONDITIONS AND EMISSIONS

	Test Series and Dates		
	Burner Modification Tests (6/30/80 to 7/12/80)	30-Day Baseline Test Average (7/15/80 to 8/17/80)	Effluent Stream Analysis (3/22/81 to 3/27/81)
Boiler Operating Conditions:			
Load (MW _e)	20.3	18.5	19.7
Excess Air (%)	18.9	20.5	23.2
Carbon Utilization (%)	99.54	99.36	99.67
Emissions:			
NO _x @ 0% O ₂ (ppm)	826	847	807
CO @ 0% O ₂ (ppm)	41	37	32
SO ₂ @ 0% O ₂ (ppm)	3364	3299	4289
SO ₃ @ 0% O ₂ (ppm)	22	25	35
CO ₂ @ 0% O ₂ (%)	18.9	18.5	18.1
O ₂ @ 0% O ₂ (%)	3.4	3.6	4.0
Hydrocarbons @ 0% O ₂ (ppm)	1	1	4
Total Particulate @ 0% O ₂ * (gr/scf)	7.98	5.93	9.83
Particulate/ash in coal (ratio)	0.965	0.828	0.812
HCN @ 0% O ₂ (ppm)	} Not Measured	} Not Measured	< 1**
NH ₃ @ 0% O ₂ (ppm)			< 1**

* 1.0 gr/SCF = 2.29 g/m³

** 1 ppm is detection limit

emissions varied due to changes in the sulfur and ash content of the coal. Hydrocarbon, HCN, and NH_3 emissions were all very low. The low CO and hydrocarbon concentrations are comparable to those observed on other Foster Wheeler boilers of similar design. The baseline NO_x emissions are about 15 percent higher than had been previously estimated by Foster Wheeler for this type of boiler.

Results of the fly ash particle distribution analysis during the three test series are shown in Figure 3-1. The particle size tests were conducted at nominal conditions during the Burner Modification Tests and Effluent Stream Analysis. Tests conducted during the 30-Day Baseline Test were at similar conditions, with load varying from 18 to 20 MW_e and excess air varying from 18 to 23 percent. The results of the size distribution measurements are very similar for each test series.

The burner register settings at nominal conditions during the Burner Modification Tests are shown in Figure 3-2. The burner core air valves were fully open. The burner adjustments were similar during the 30-Day Baseline Test and Effluent Stream Analysis. As shown in Figure 3-2, the upper registers are more open than the lower registers. These settings have been found to produce the most uniform flame shapes on all four burners at nominal operating conditions. At nominal conditions, the flames from all burners stabilized close to the throat exit (within 5cm[2 in.]). This flame shape is similar to the shape observed during the Intervane Burner tests in the LWS at EER. The WIPCO furnace was filled with luminous combustion products, making it difficult to delineate specific flame boundaries. The flames did not appear to impinge on the rear wall or on the side walls adjacent to Burners 1 and 3 (north wall). However, the flame from Burner 4 was observed to roll along the adjacent side wall (south wall). The side wall adjacent to Burner 2 could not be observed due to the location of the observation port.

To determine combustion conditions within the furnace, O_2 and CO conditions were measured at the furnace walls using sample taps installed prior to the baseline testing. Average gas concentrations with normal full load operation during the Burner Modification Tests are shown in Table 3-3.

These measurements confirm that reducing conditions (low oxygen and high CO) existed in the areas adjacent to Burners 2 and 4. This corresponds to the

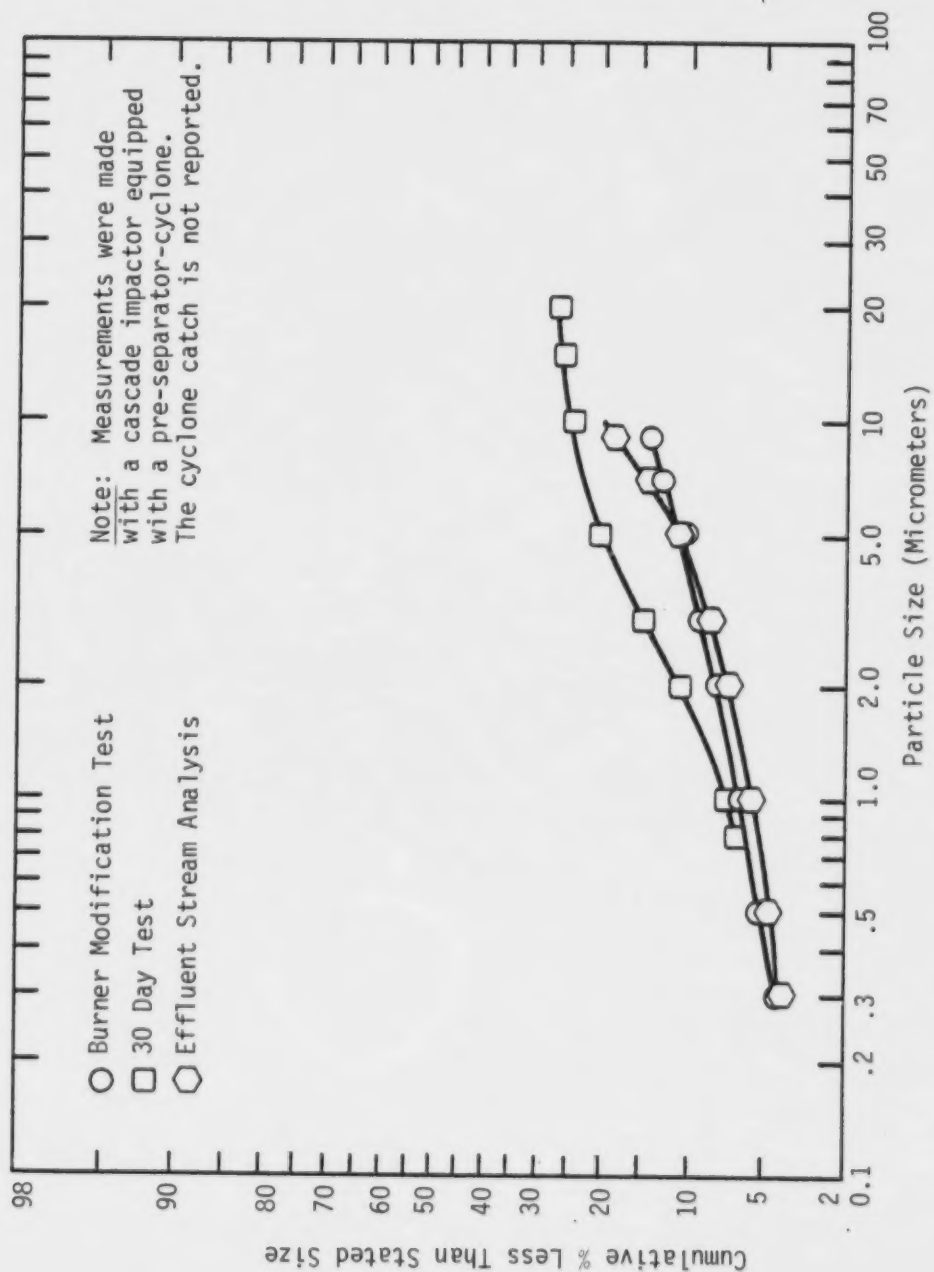


Figure 3-1. Results of fly ash particle size distribution analysis.

Note: Burner Locations as Viewed from Rear of Windbox.

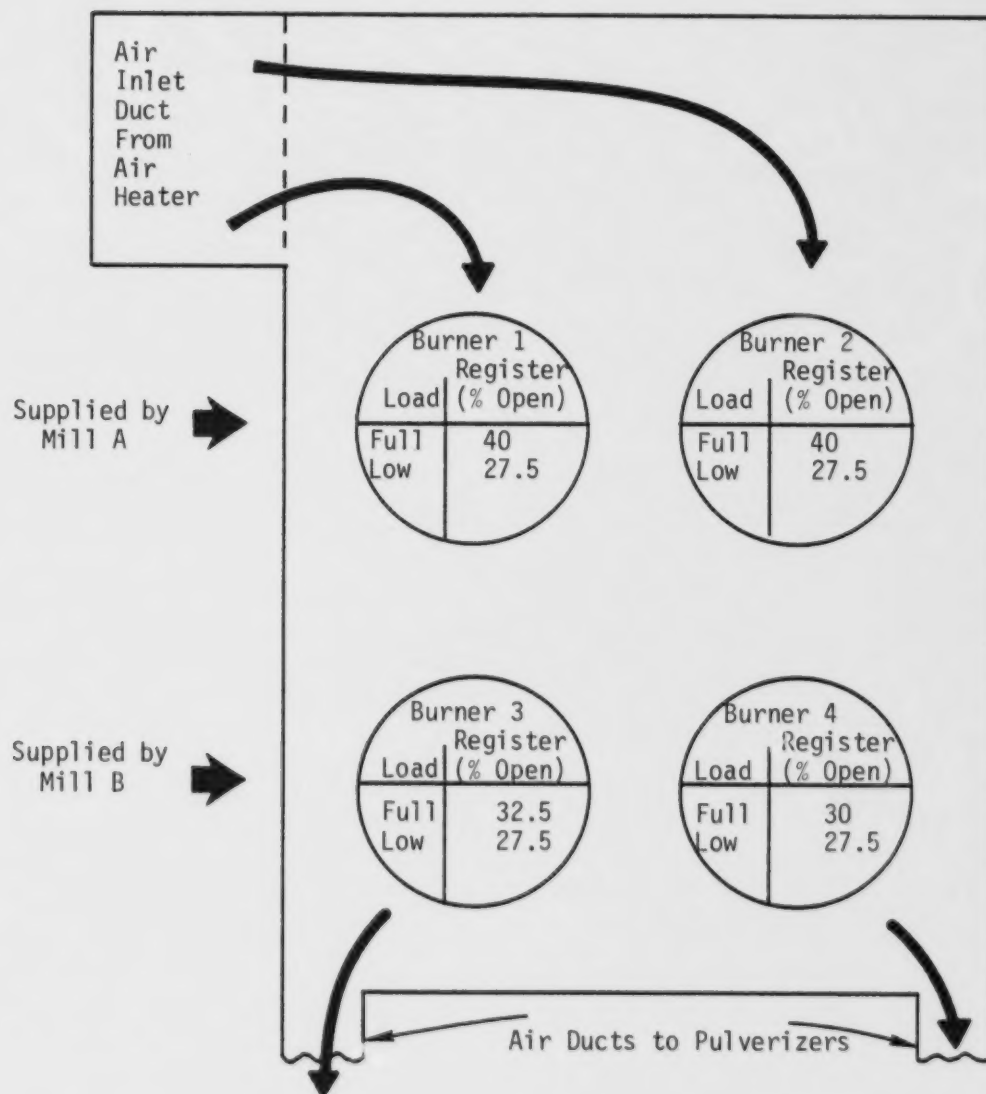


Figure 3-2. Normal register adjustment.

TABLE 3-3. FURNACE WALL GAS COMPOSITION DURING BURNER
MODIFICATION TESTS

Species	Furnace Walls		
	Adjacent to Burners 1 & 3 (North Wall)	Adjacent to Burners 2 & 4 (South Wall)	Rear Wall
O ₂ as measured (%)	2.4	0.2	3.0
CO @ 0% O ₂ (ppm)	202	>2000	202

areas where the flame was observed to contact the furnace wall. Measurements of the same gases at the twelve probe locations upstream of the air heater resulted in essentially uniform results. Thus, the variations in gas concentrations exiting the burner zone are effectively smoothed out in the upper furnace and convective pass. Various register adjustments proved unsuccessful in producing symmetrical flames and Foster Wheeler has advised that this condition is unusual. Similar furnace wall concentrations were noted throughout the 30-Day Baseline Test. During the Effluent Stream Analysis, however, O_2 and CO concentrations on the south wall were similar to those on the other walls, as shown in Table 3-4, although some flame impingement was noted. This change in gas concentration suggests that the cause of the reducing conditions noted at the south wall was related to a change in the performance of the fuel firing system between the 30-Day Baseline Test and Effluent Stream Analysis. Changes in the performance of the coal pulverizers could have such an effect due to nonuniform distribution of coal to the burners.

3.2 Operating Range

A key objective of this demonstration program is to provide information on the ability of the low NO_x burners to operate satisfactorily over a range of boiler operating conditions comparable to the original equipment burners. Therefore, as part of the Burner Modification Tests, boiler operating conditions (load, excess air, and burner adjustments) were varied to determine the range of operation achievable by the original equipment burners. Following the Burner Modification Tests, the boiler was operated over the normal duty cycle during the 30-Day Baseline Test to evaluate the range of operating conditions typically required by the boiler operators.

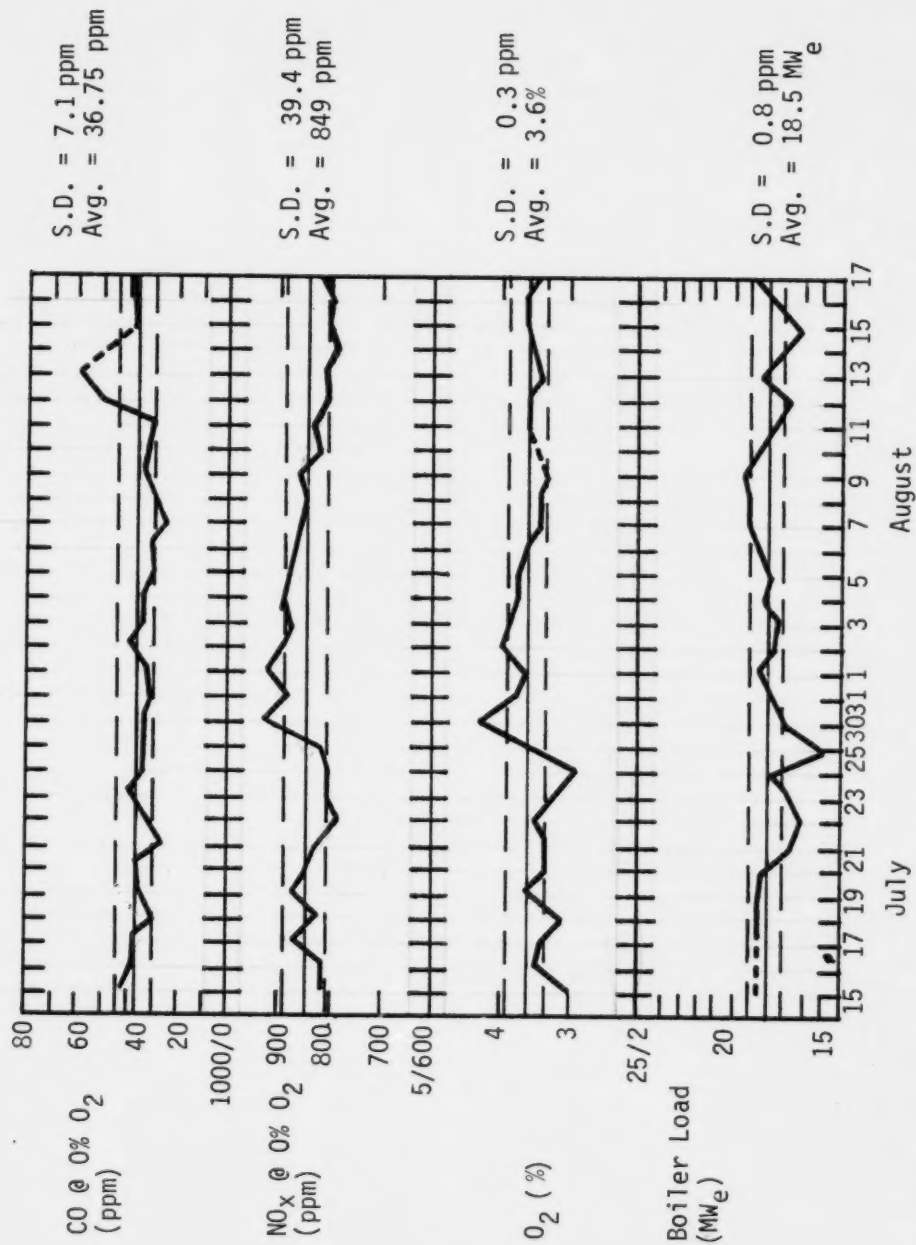
Table 3-5 shows the range of operating conditions used by the boiler operators during the 30-Day Baseline Test compared to the range achieved during the Burner Modification Test. The WIPCO unit is primarily baseloaded and the boiler normally operates over a limited range of conditions. Changes in operating conditions during the 30-Day Baseline Test were related to changing load requirements. At reduced loads, the boiler is typically operated at high excess air and with the burner registers closed from the nominal full load conditions. Figure 3-3 shows the daily averages of NO_x , CO, O_2 , and boiler load during the 30-Day Baseline Test. NO_x concentrations showed only minor changes in excess air. CO concentrations were essentially constant during the tests.

TABLE 3-4. FURNACE WALL GAS COMPOSITION DURING EFFLUENT STREAM ANALYSIS TEST

Species	Furnace Walls		
	Adjacent to Burners 1 & 3 (North Wall)	Adjacent to Burners 2 & 4 (South Wall)	Rear Wall
O ₂ as measured (%)	2.7	2.4	3.0
CO @ 0% O ₂ (ppm)	434	138	84

TABLE 3-5. RANGE OF OPERATING CONDITIONS ACHIEVED DURING THE BURNER MODIFICATION TESTS COMPARED TO THE 30-DAY BASELINE TEST

Operating Variable	Range of Operation	
	30-Day Baseline Test	Burner Modification Test
Load (% of Full Load)	75 to 101	66.5 to 105.5
Excess Air (%)	13.5 to 30	13.3 to 31.5
Register Position (% Open from Normal)	-10 to 0	-10 to +5
Core Air (% Open)	100	55.6 to 100
Mill Bias (% Bias)	0	0 to 26



Note: Boiler shut down from July 25 to July 30, 1980 for unscheduled outage unrelated to 30 day test.

Figure 3-3. 30-Day Baseline Test results.

During the Burner Modification Tests, it was possible to operate the boiler over a load range of 13 to 21 MW_e. The maximum load was limited by steam condenser capacity. The minimum load was determined by increasing flame instability with decreasing load. The reasons for the instability are not known but may be due to the inability of the coal feeders to operate at low feed rates. The feeders at WIPCO are oversized. At loads less than 15 MW_e the operators have observed that the feed rate can vary erratically.

The minimum excess air achieved during the Burner Modification Tests was specified by the WIPCO management based on their experience that the flame may become unstable at lower loads. However, at the minimum excess air (13.3 percent) operating condition the flames appeared stable and CO levels did not increase. This indicates that lower excess air levels may have been possible. The maximum excess air (31.5 percent) allowed an accurate evaluation of the slope of the NO_x versus excess air curve without reducing boiler efficiency significantly. The core air valve adjustment from 90° open to 50° open (nominal condition) to 50° open drew the flame into the throat approximately 5 cm (2 in.), therefore limiting further core air valve closing. The range of mill bias was limited by minimum feeder speed on the mill supplying the upper burners. The range of variation in register positions from the baseline was controlled by the flame stand-off distance as indicated by the main flame scanner. Opening the registers more than 5 percent from baseline caused the base of the flame to move out into the furnace (increased flame stand-off), resulting in a loss-of-flame indication. Closing the registers more than 5 percent from baseline drew the flame back into the throat. Operation at this condition is normally avoided due to the potential for slag formation in the burner exit and/or coking or overheating of the nozzle.

In addition to these operating conditions, the feasibility of operation with only one mill (two burners) in service was tested. It was found that the WIPCO boiler could not be operated with only one mill in service without supplementary oil firing for flame stability. Attempts to shut-off the supplementary oil firing with two burners in service resulted in a loss-of-flame indication on the flame scanning system. FW service personnel have visually observed

the flames and determined that the problem is caused by the main flame scanner being located within the core region. This is not recommended by FW and was done by the scanner's supplier. Under some conditions the coal skirt formed by the annular nozzle shades the scanner so that a false loss of flame signal is received and the mill is tripped. This has occurred in the presence of FW personnel even though a satisfactory flame was visually observed.

3.3 Effects of Operating Conditions on Emissions

Operating conditions and burner adjustments evaluated during the burner modification test included load (firing rate), excess air, core air valve settings and register positions. The range of emissions measured during the Burner Modification Tests is listed in Table 3-6.

Tests of other commercial burners have shown that the relationships between NO_x emissions, firing rate and excess air are approximately linear over the normal operating ranges. Consequently, data from the Burner Modification Tests with the nominal core air valve and register settings was fitted to a linear relationship using a least squares technique. The result was the following correlation:

$$\text{NO}_x @ 0\% \text{ O}_2 \text{ (ppm)} = 2.30 \times (\% \text{ Full Load}) + 9.30 \times (\% \text{ Excess Air}) + 427.7$$

Figure 3-4 shows the relationship between NO_x emissions and firing rate (load) at constant excess air. All data points were corrected to the design point excess air (18 percent) using the correlation. All the data lie within a band of ± 25 ppm except for the point at 67 percent load which is about 75 ppm low. It should be noted that this point was obtained while firing exceptionally wet coal and this may have affected NO_x emissions.

Figure 3-5 is a cross-plot showing the effect of excess air at constant firing rate. All data points were corrected to 100 percent load using the correlation. Again, all data points lie within a ± 25 ppm band of the correlation except for the low load point.

CO emissions were insensitive to load and excess air over the range evaluated. Figure 3-6 shows the effect of load on CO emissions for a subset of the data within the range 17 to 20.5 percent excess air. There appears to be no systematic effect of excess air. The data scatter is about ± 10 ppm from the average of 40 ppm. The effects of excess air are shown in Figure 3-7.

TABLE 3-6. RANGE OF GASEOUS EMISSIONS

Species	Range of Emissions Concentration @ 0% O ₂ , dry
O ₂ (%)	2.5 to 5.1
NO _x (ppm)	670 to 955
CO (ppm)	30 to 53
CO ₂ (%)	17.2 to 18.8
SO ₂ (ppm)	3043 to 3805
HC (ppm)	0 to 3

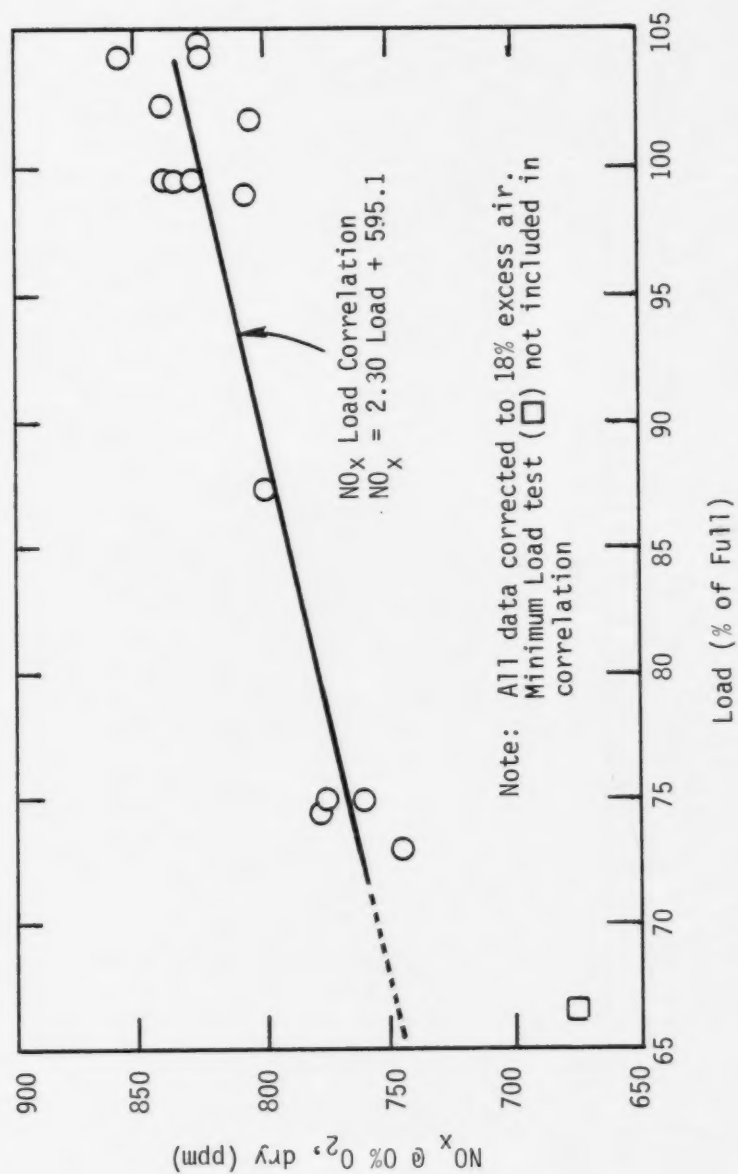


Figure 3-4. Effect of load on NO_x.

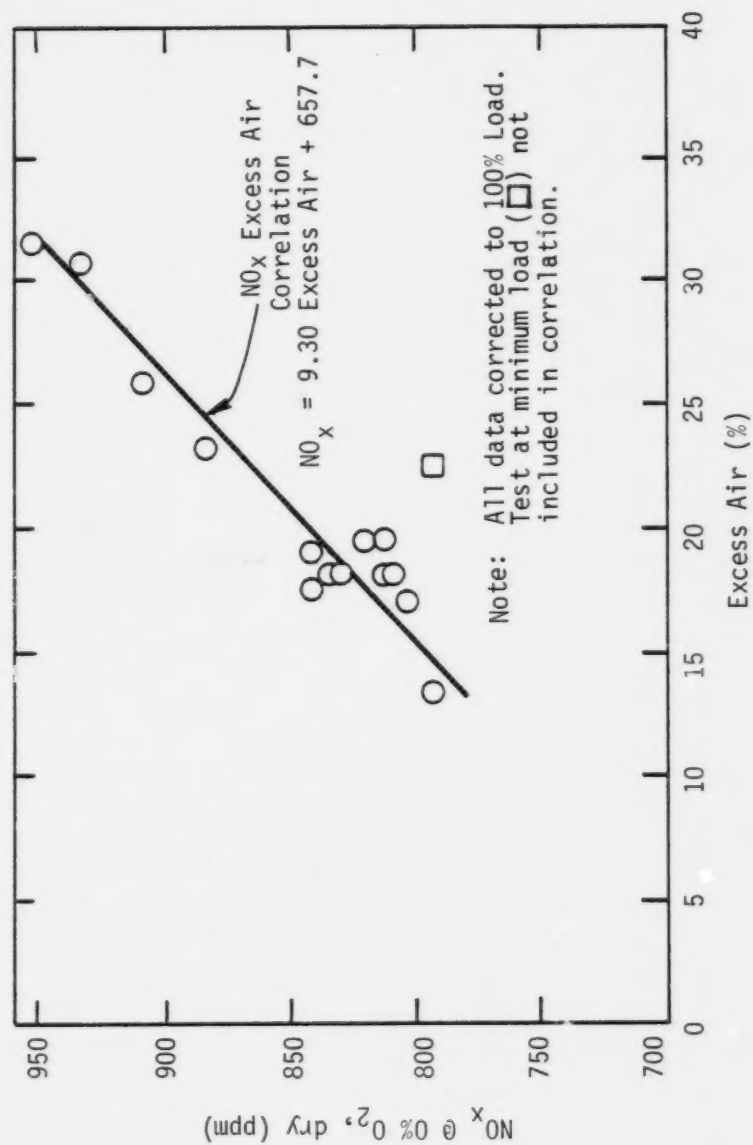


Figure 3-5. Effect of excess air on NO_x.

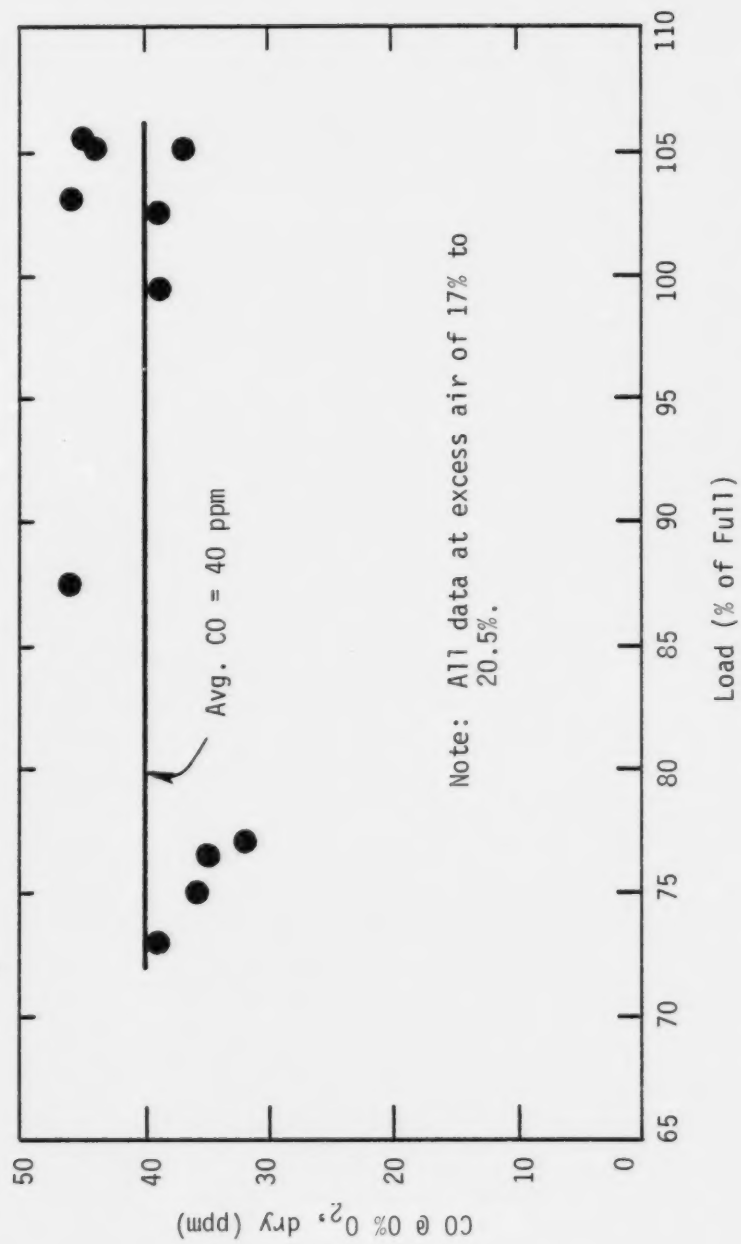


Figure 3-6. Effect of load on CO.

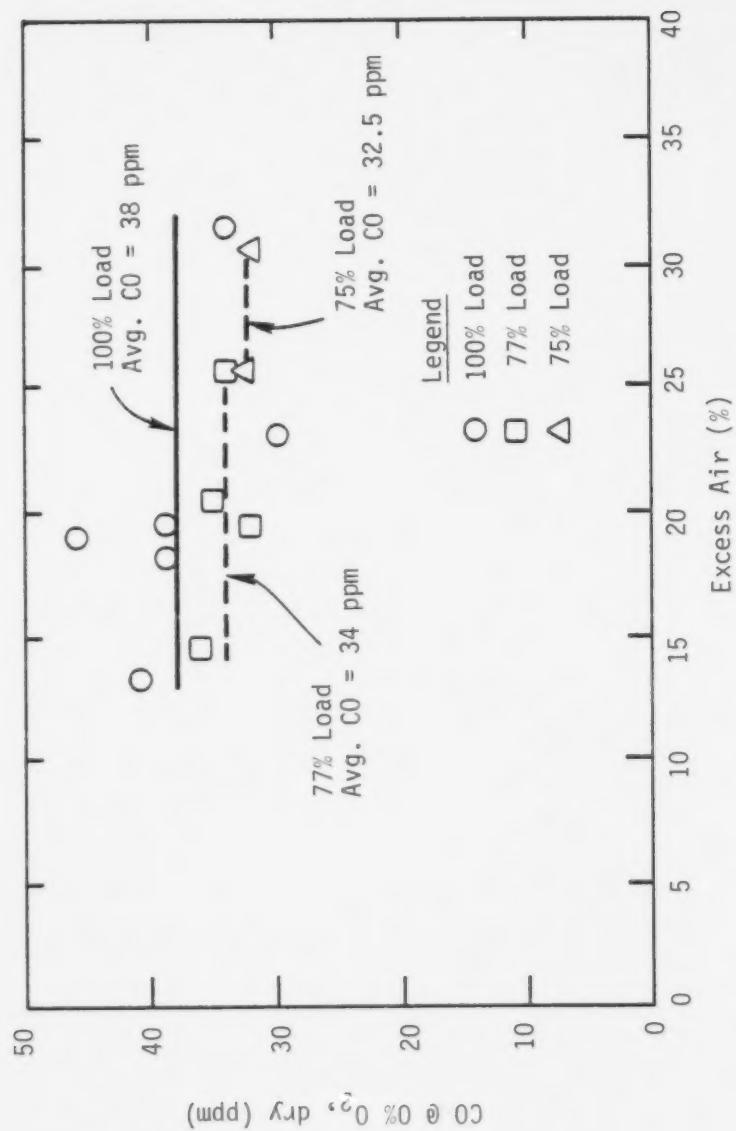


Figure 3-7. Effect of excess air on CO.

Although the averages for the three load ranges vary somewhat, the differences are within the range of data scatter.

The effect of core air valve position was evaluated at 65 and 100 percent load and nominal excess air. Closing the core air valve from the normal full open position caused the flame to retract into the burner throat. The effects on NO_x emissions are shown in Figure 3-8. All data points have been corrected to 18 percent excess air. At full load, closing the core air valve increased NO_x emissions. At low-load the effect is unclear. In comparison with the NO_x correlation which applies to the full open core air valve position, closing the core air valve decreases NO_x emissions, the opposite of the effect at full load. However, in comparison to the data point at 67 percent load with the core air valve full open, closing the core air valve increases NO_x emissions. Note that the data point at 67 percent load with the core air valve open was not included in the correlation.

The effects of register position were evaluated at the same loads as the core air valve. However, only small changes in register position were made due to the pronounced effects on flame characteristics. Closing the registers drew the flame back into the throat in the same manner as closing the core air valve. Opening the registers increased the flame stand-off distance, resulting in a loss-of-flame indication. The effect on NO_x emissions is shown in Figure 3-9. At full load the nominal operating condition produced the lowest NO_x emissions. Opening or closing the registers from the baseline settings increased NO_x emissions. The interpretation of the effect of register position at low load is subject to the same problem as the core air valve effect: the NO_x emissions for the nominal setting are considerably lower than the correlation.

The effects of core air valve and register variations on CO emissions are shown in Figure 3-10. CO emissions appears to be independent of the burner settings at high and low load.

Particulate concentrations were measured over a range of load, excess air as well as mill bias. However, no relationship between particulate emissions and operating conditions was apparent. Figure 3-11 shows a graph of particulate results for the three test series versus excess air. Particulate results are expressed as the ratio of particulate mass to mass of ash in the coal to compensate for varying ash concentrations in the coal. Although the particulate

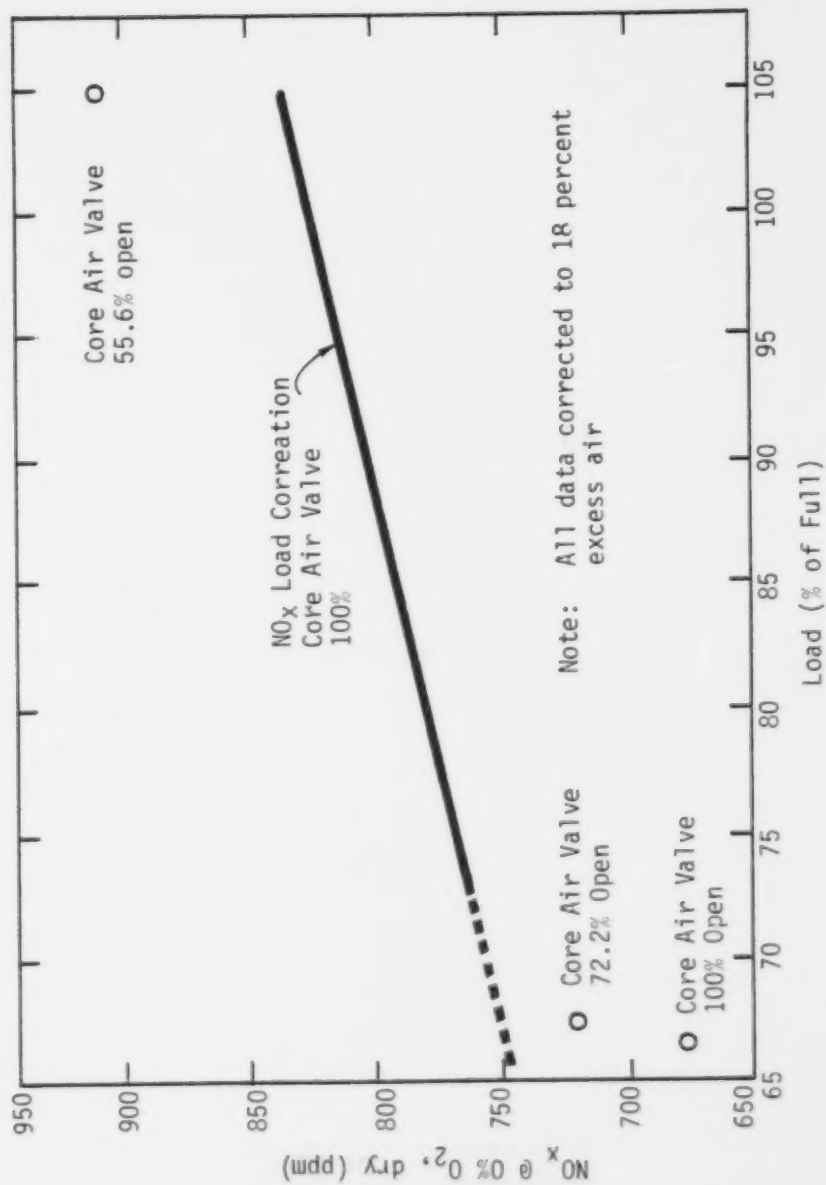


Figure 3-8. Effect of core air valve setting on NO_x.

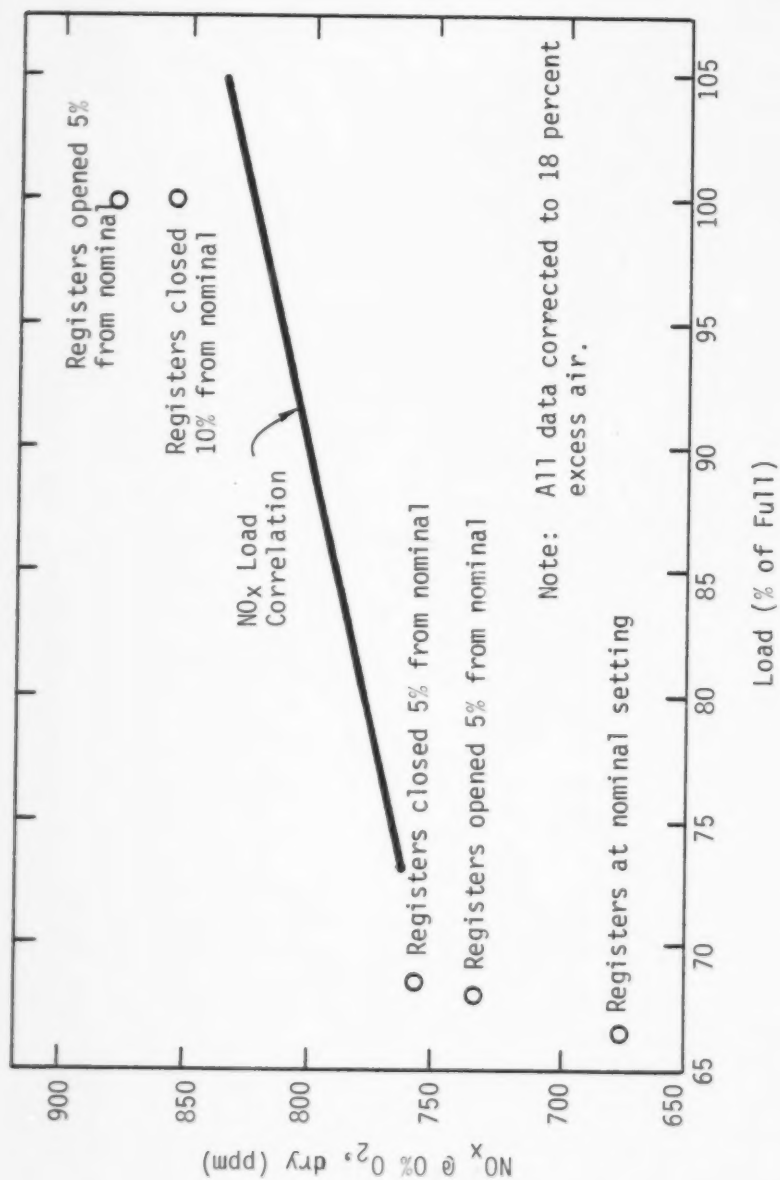


Figure 3-9. Effect of register position on NO_x.

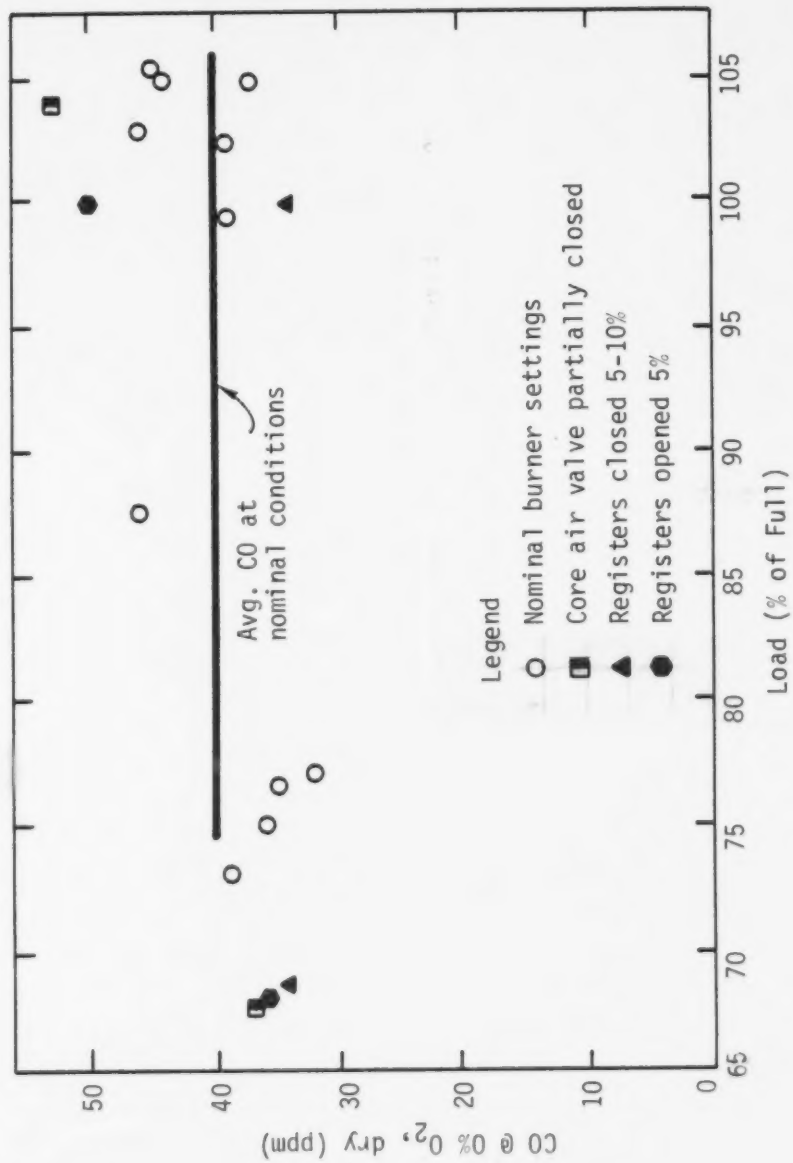


Figure 3-10. Effect of register and core air valve settings on CO.

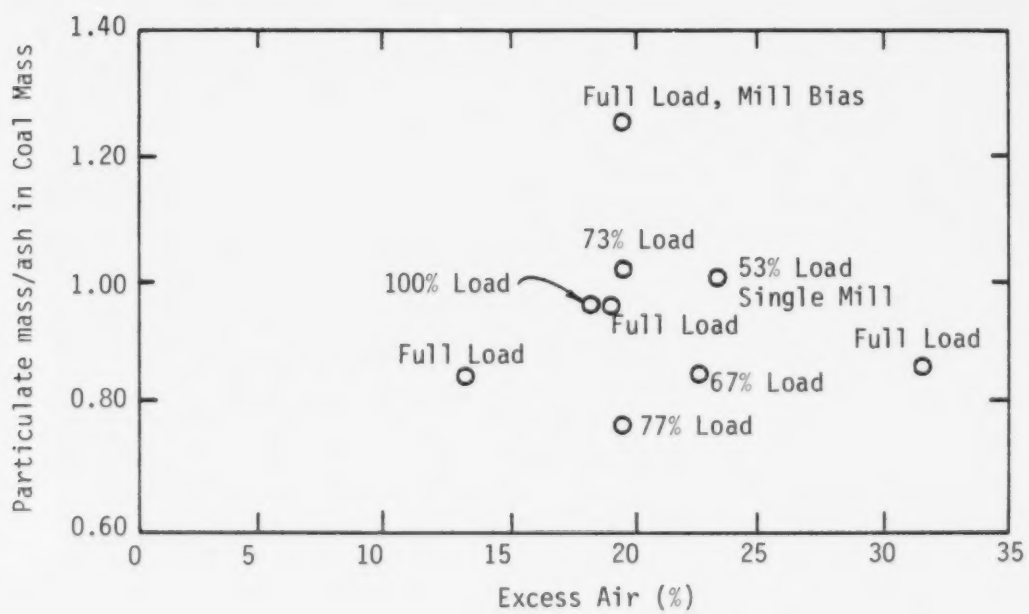


Figure 3-11. Particulate test results.

concentration was higher during the mill bias test, carbon utilization in this test was comparable to other test conditions. Thus, the higher particulate is probably due to measurement rather than an increase in particulate. The particulate emissions were primarily affected by variations in the ash content of the coal. Figure 3-12 shows the similarity of particulate concentration changes to coal ash content changes. Carbon utilization was calculated from carbon and ash analyses of coal and particulate samples for each particulate samples for each particulate test. The carbon utilization varied from 99.12 to 99.67 percent during the three test series, thus showing high combustion efficiency for each test. F
3-12

Particle size distribution was measured at full and reduced load during the Burner Modification Tests. No change in size distribution was noted due to the change in load. Figure 3-13 compares the size distribution measurements at full load and 70 percent of full load. 3-13

3.4 Low NO_x Operation

The objective of this program is to demonstrate the reductions in NO_x emissions which can be achieved by retrofitting the distributed mixing burners. The reductions in NO_x emissions will be measured from the minimum NO_x emissions which can be achieved without burner replacement or other major modifications. During this test series, low excess air and bias firing were evaluated as possible combustion modifications to reduce NO_x emissions.

As previously discussed, the minimum excess O₂ level tested was 2.5 percent, corresponding to an excess air level of 13.5 percent. At this condition, combustion was satisfactory and the NO_x emissions were reduced to 796 ppm, a 4 percent reduction from the baseline (826 ppm). This is an insignificant reduction.

Bias firing involves operating the upper and lower burners at different firing rates and/or excess air levels. This was achieved by varying the coal feed rates to the two pulverizers which supply the upper and lower burners separately. The coal feed rate to the lower burners was increased while the coal feed rate to the upper burners was decreased maintaining the total coal feed rate constant. The net effect was firing a majority of the coal through the lower burners at low excess air while providing additional air through the

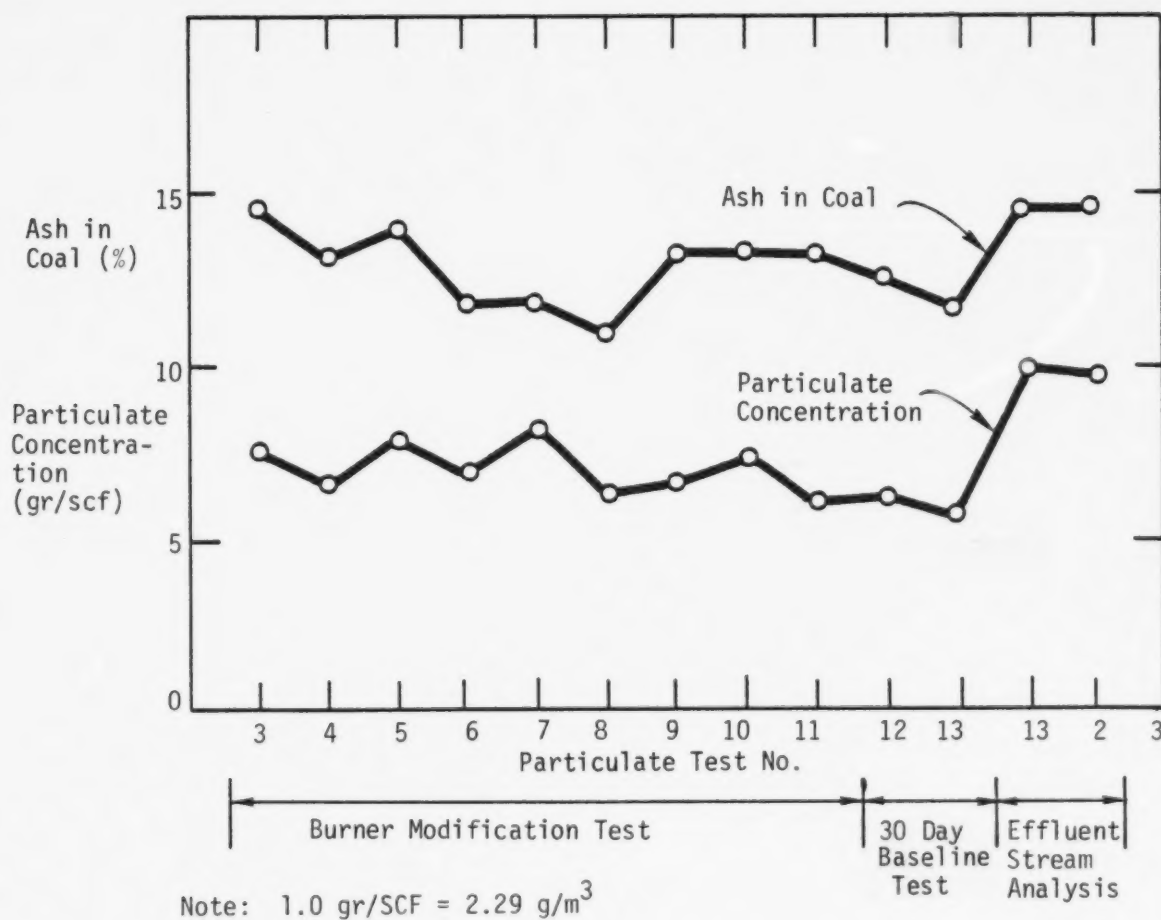


Figure 3-12. Relationship of ash in coal to particulate concentration.

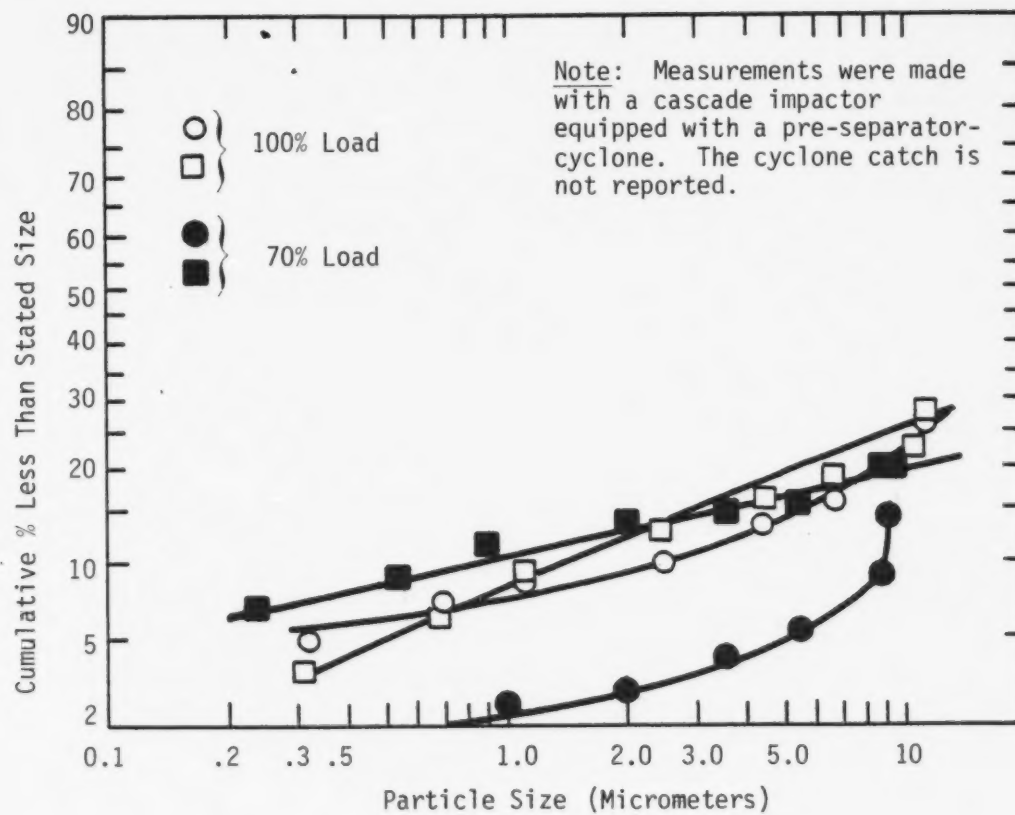


Figure 3-13. Comparison of fly ash particle size distribution at 100 percent and 70 percent of full load.

upper burners to complete combustion. This partial staging reduced NO_x emissions as shown in Figure 3-14. The maximum bias was limited by the minimum feeder speed on the mill supplying the upper burners. The stoichiometry at the lower burners decreased as the bias increased to 95 percent theoretical air (substoichiometric) at the maximum bias. The effects of biasing the registers was also evaluated. The registers of the bottom burners were closed 5 percent from the nominal settings. However, NO_x emissions increased as shown in Figure 3-14.

As the mill bias was increased, the ignition point of the lower flames was observed to move slightly out of the exit (2 to 3 inches) and the path of unburned coal and air passing through the exit appeared darker than normal. The flame volume also increased and the flames were observed to roll along both sidewalls. The concentrations of O_2 and CO measured at the sidewalls showed almost no O_2 and very high CO levels. However, the CO in the exhaust remained low even at the maximum bias, as shown in Figure 3-15.

The maximum bias resulted in a 19 percent reduction from the baseline (826 ppm). This is a significant reduction, but sustained operation at this condition is not desirable. Ash fusion temperatures are lower under reducing conditions and this could cause furnace slagging and related corrosion.

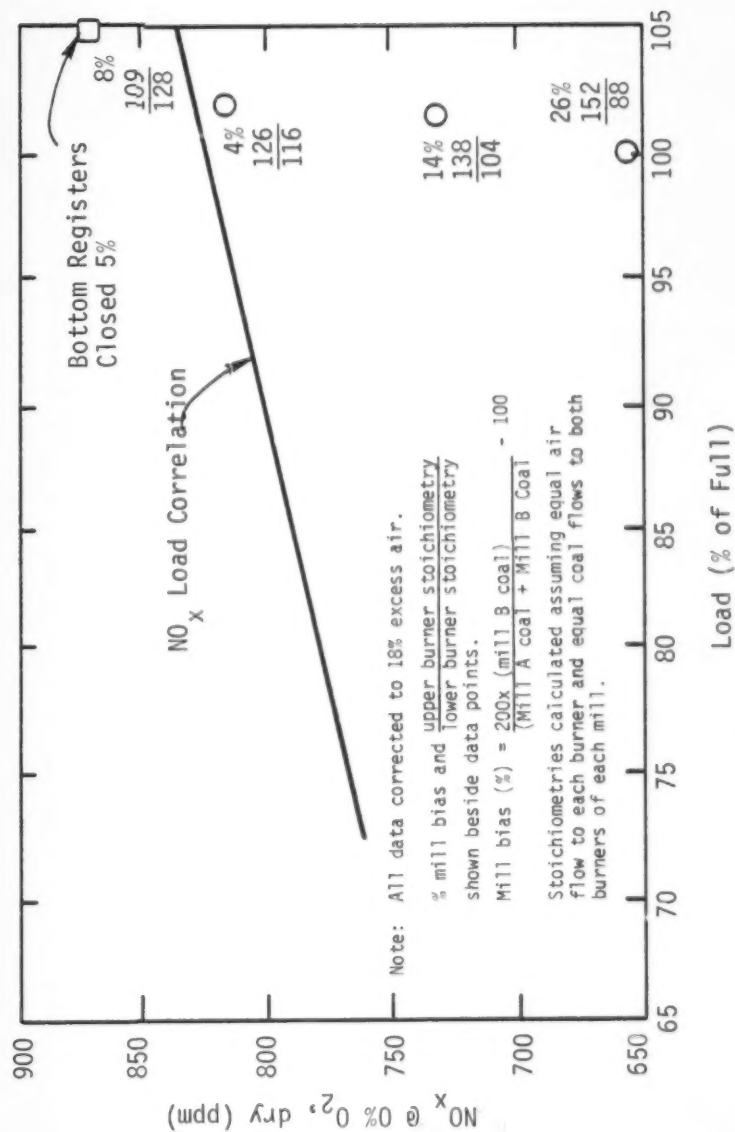


Figure 3-14. Effect of bias firing on NO_x.

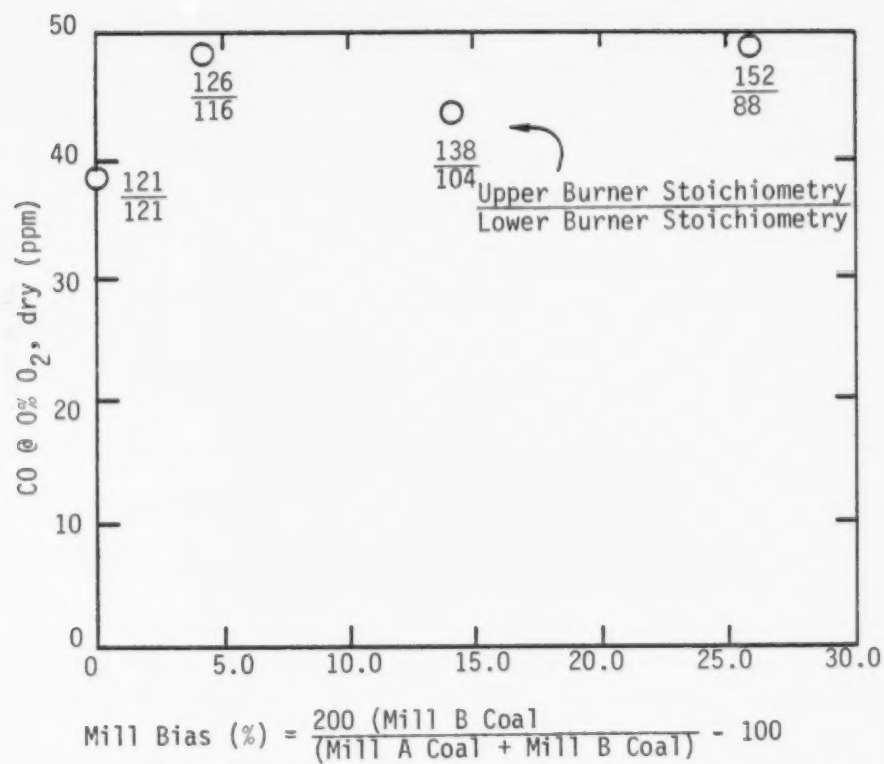


Figure 3-15. Effect of bias firing on CO.

4.0 DMB FIELD EVALUATION

The WIPCO host boiler has been retrofitted with DMBs. The burner, tertiary air ports and control system were installed in the spring and summer of 1981. The burner and tertiary air port installation required about five weeks and was within a few days of the time estimated by Foster Wheeler. However, difficulty was encountered in interfacing the control system with the host boiler equipment. This extended the outage period considerably. For the remainder of the third year (ending November, 1981), the burners were operated with the tertiary air ports closed (only leakage air passing through). Performance optimization tests under staged conditions are scheduled to begin during the fourth year.

The DMBs installed at WIPCO are based on the design of Prototype 2 which was tested in the LWS. The registers, coal nozzle and burner exit are identical except that the materials of construction, fasteners, etc., for the WIPCO burners have been upgraded to Foster Wheeler commercial standards for field operating equipment. The tertiary air port array installed at WIPCO is designed to match the tertiary air velocity used in the prototype tests. However, due to the multi-burner configuration and structural constraints the number and location of ports is considerably different. The following subsection discusses the design and installation of the burners at WIPCO.

The combustion air for the core air passage, registers and tertiary air ports is supplied from a common windbox. The airflow distribution among these passages is measured and controlled by devices on each passage. The devices on the central portion of the burner including the core and secondary air registers were calibrated during the second year of the program, and the results were discussed in the Second Annual Report. The devices on the tertiary air ports were calibrated during the third year. Section 4.2 discusses these calibrations and the method which will be used to control the air flow distribution on the DMBs installed at WIPCO.

4.1 Burner Design and Boiler Modifications

The prototype DMB for the WIPCO field evaluation was designed by integrating the DMB design criteria and host boiler characteristics with Foster Wheeler burner components. The characteristics of the WIPCO unit were found to be compatible with the DMB design criteria except for the following:

- Windbox depth and burner exit length
- Throat diameter
- Burner spacing and structural constraints
- Controls

These incompatibilities were solved by modifying the burner design and altering boiler and windbox structures as discussed below.

The windbox of the WIPCO unit was designed to accommodate the original equipment Intervane Burners. Figure 4-1 shows the Intervane Burner and windbox geometry. Note that there is ample space for combustion air to flow around the burner components. Figure 4-2 shows the installation of a DMB meeting the design criteria. The two register assemblies and large exit occupy essentially all of the windbox. Foster Wheeler determined that the resulting blockage would prevent adequate combustion air flow to the burners. Consequently, a compromise prototype burner was designed by greatly reducing the exit length. This compromise burner was the initial Prototype burner (Prototype 1) and was shown in Figure 2-1. Prototype 1 was tested in the LWS to optimize the burner settings. These tests showed that the flame was unstable at the design point. The instability may have been due to the short exit length or the use of DMB design parameters which were developed for a burner with a central coal nozzle instead of the annular Foster Wheeler nozzle. Prototype 1 was modified by incorporating the Foster Wheeler Controlled Flow Burner exit geometry (Prototype 2). Subsequent tests of Prototype 2 in the LWS confirmed that the flame was stable at the design point and that the overall performance of the burner met the host boiler requirements.

The throat diameter of the prototype DMB is considerably larger than the throat diameter of the Intervane Burner as shown in Figure 4-3. Since the Intervane burner throat was formed by a thin layer of refractory over studded water-wall tubes, there was no way to accommodate the DMB throat without modifying the boiler-tube wall. Six additional tubes needed to be bent.

The arrangement of the Intervane burners on the front wall is shown in Figure 4-4. The combustion air enters the windbox from the top, flows to the burners and the remainder is ducted out the bottom corners of the windbox to the pulverizers. The desired arrangement of the DMBs and tertiary air ports is shown in Figure 4-5. This arrangement produces the 50 ft/sec DMB design criteria velocity through each port with a mass flow distribution equivalent

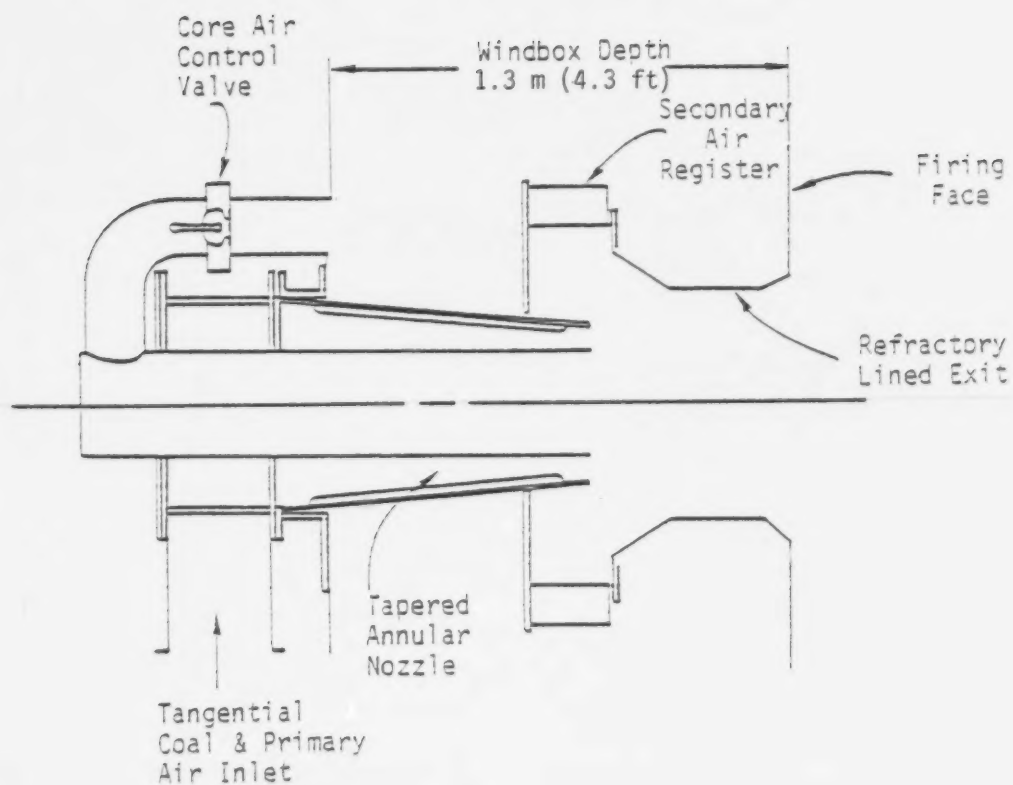


Figure 4-1. Foster Wheeler Intervane burner in WIPCO windbox.

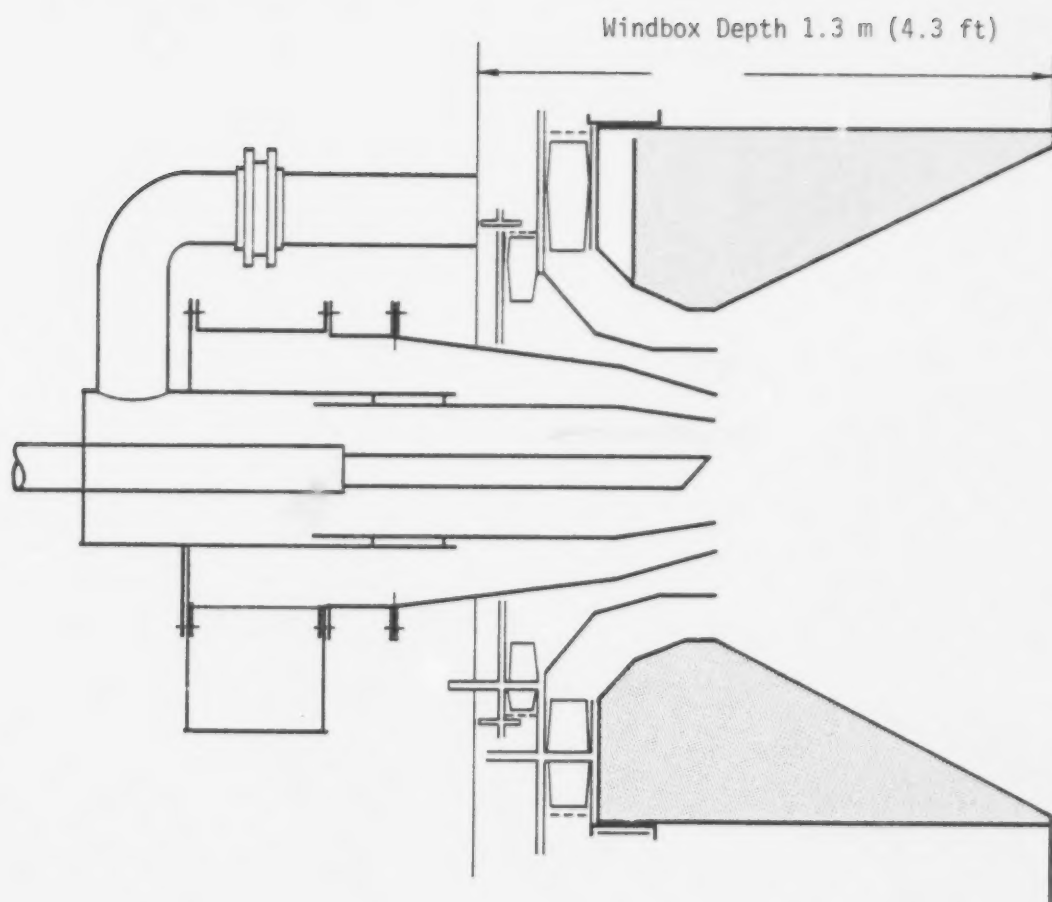


Figure 4-2. DMB meeting design criteria in WIPCO windbox.

Note:

1. All dimensions in inches.
2. 1.0 inches = 2.54 cm

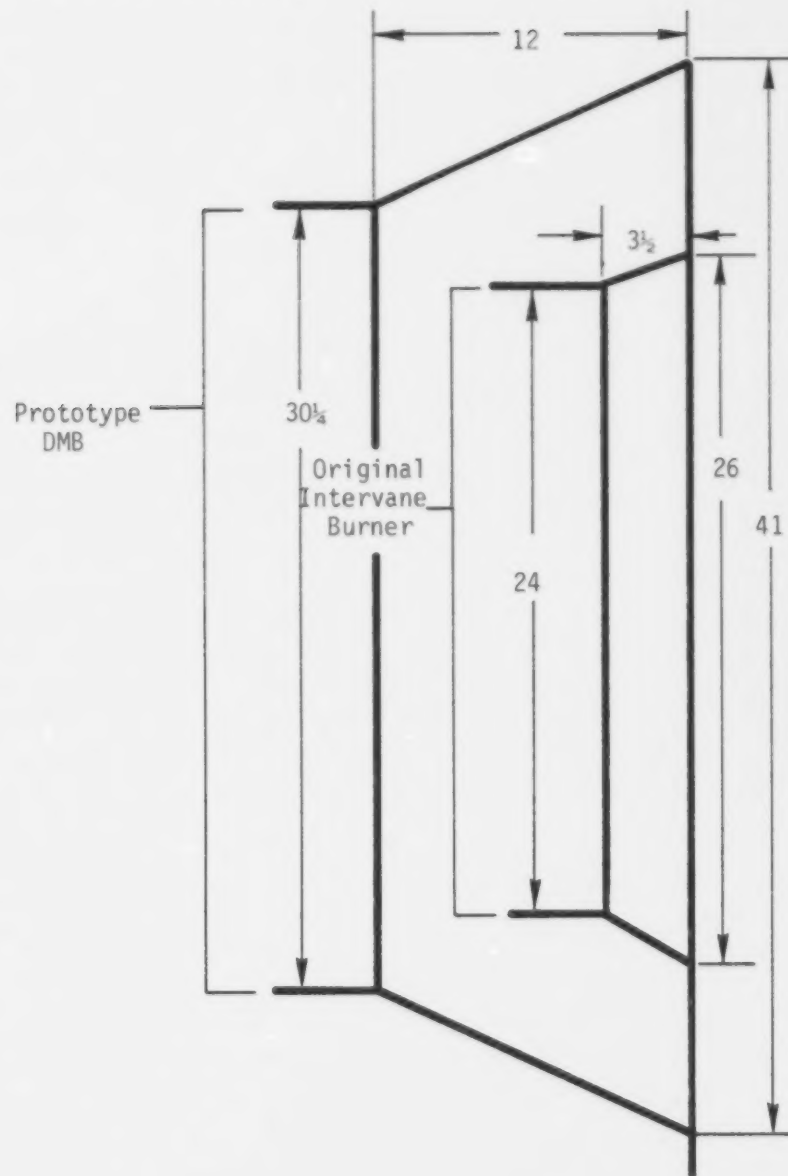


Figure 4-3. Comparison of DMB and Intervane burner exit geometries for WIPCO Pearl Station.

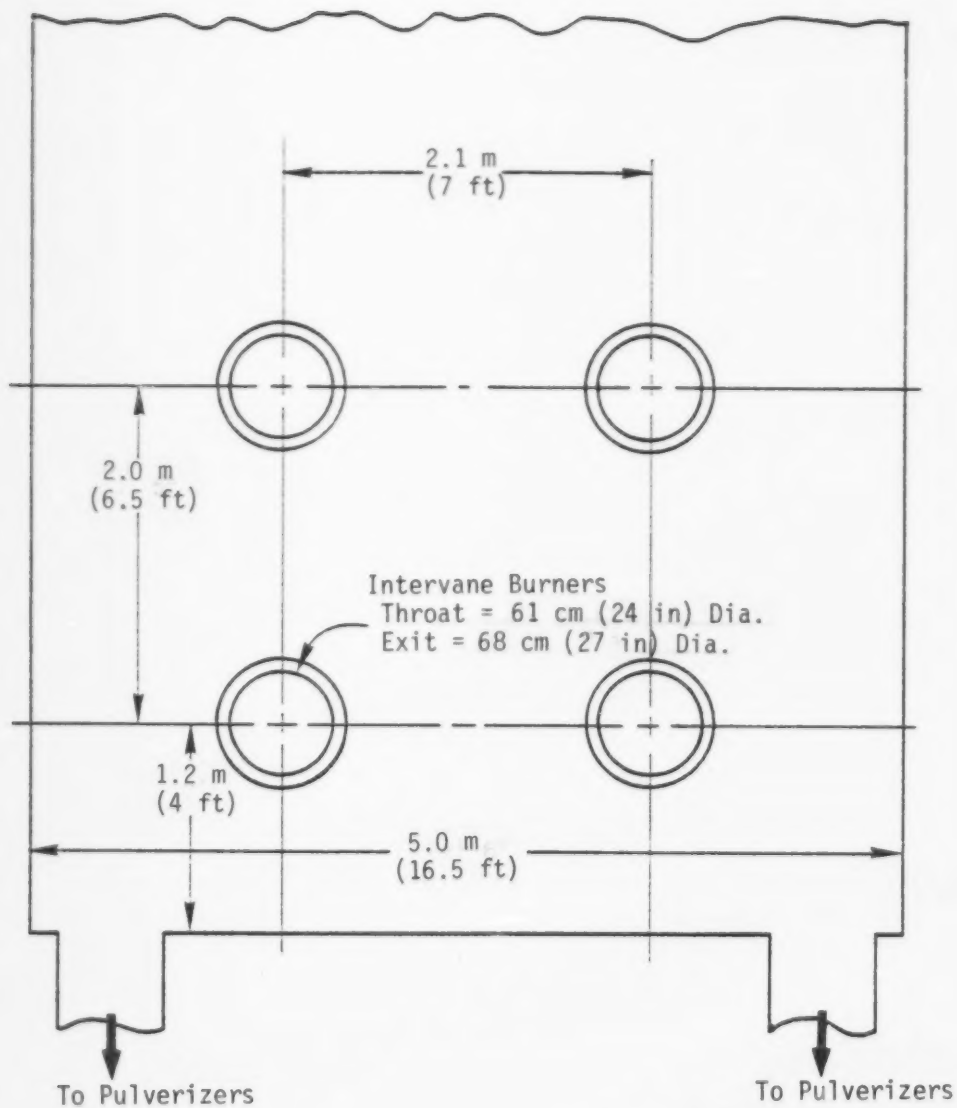


Figure 4-4. Original WIPCO burner arrangement

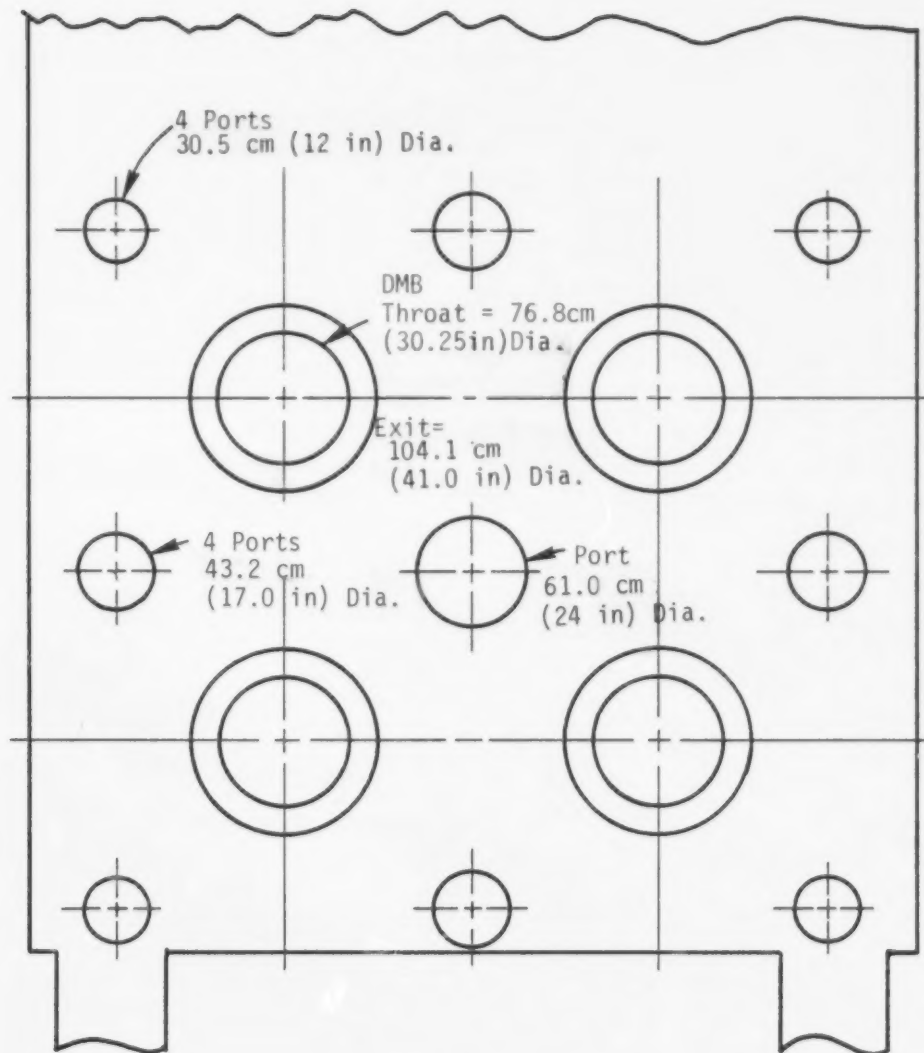


Figure 4-5. Desired DMB arrangement.

to having each burner surrounded by four separate parts. For example, the port in the center has four times the area of the corner ports since it contributes to four burners. For the prototype burner tests, four tertiary air ports were arrayed around the burner with the same spacing as in the array in Figure 4-5. However, all four ports were 30.5 cm (12 in) diameter.

This tertiary air port arrangement distributes the air uniformly around each burner at the velocity specified by the DMB design criteria with a minimum number of ports. However, applying this array to the WIPCO unit causes the following structural problems:

- interference with buckstays
- interference with windbox trusses
- interference with pulverizer air supply ducts
- elimination of hopper support tubes

The WIPCO unit is designed with buckstays between, above, and below the burners. Installation of the ports would interfere with all three. The windbox front-face and the outboard portions of the burner are supported by several trusses in the windbox. The ports and control mechanisms interfere with several trusses. The two bottom corner ports are directly over the pulverizer supply ducts. Control systems for the ports would interfere with air flow to the pulverizer. Finally, the additional tube bends required for the ports affect almost all of the remaining straight tubes which normally support the hopper.

After considerable analysis and discussion by EER, EPA and Foster Wheeler, the compromise port arrangement shown in Figure 4-6 was selected. This arrangement distributes the tertiary air around and between the burners while minimizing structural problems. The ports above the burners are the maximum size that will clear the buckstay. The port in the center is reduced in diameter to allow clearance for its control mechanism between the burner registers. The ports along the sides have been moved to allow free flow into the pulverizer ducts. The bottom of the windbox has been lowered to provide a plenum for installation of the lower ports.

The structural problems which could not be eliminated are as follows:

- Front Wall Replacement - Due to the large number of complex tube bends the entire front wall had to be replaced.

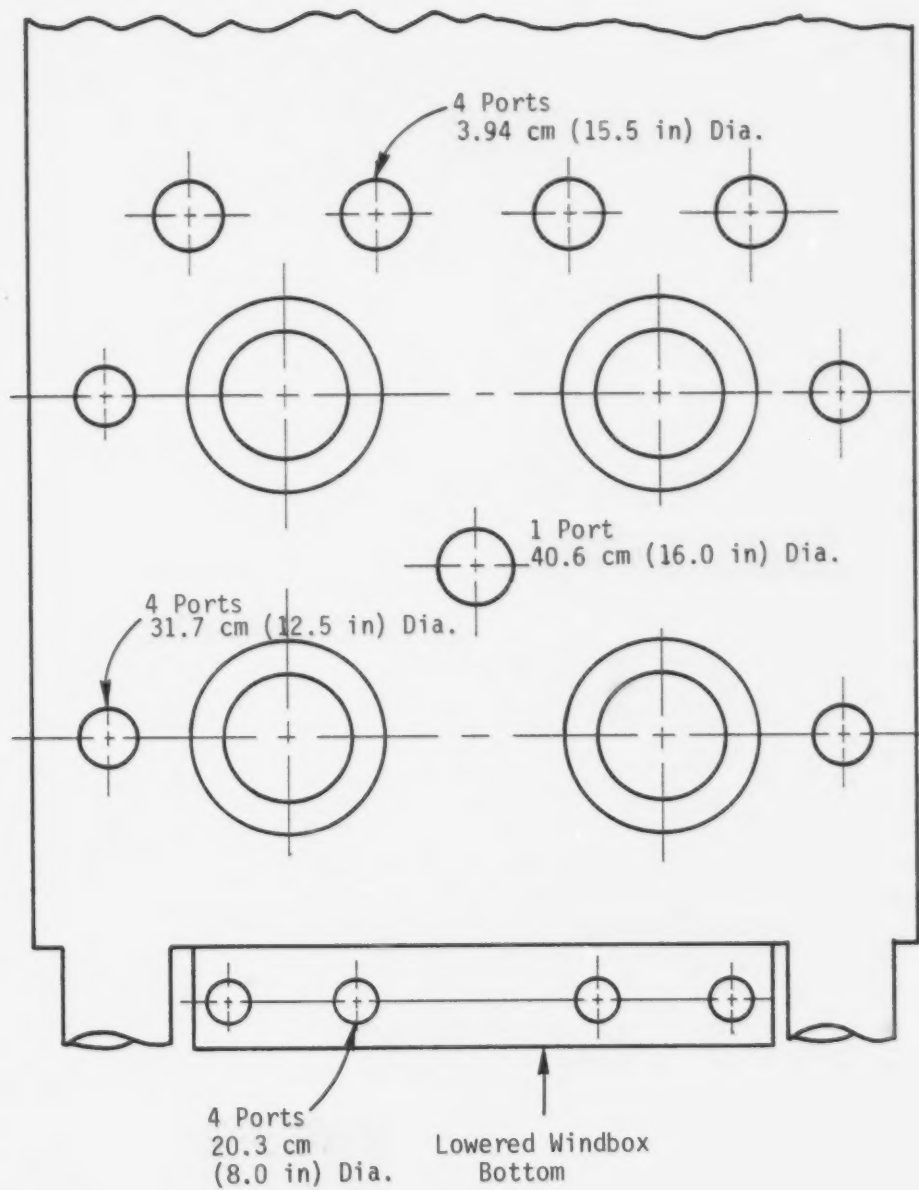


Figure 4-6. Final compromise port arrangement.

- Buckstay Removal - The buckstay between the burners had to be removed and additional windbox structures were constructed to handle the pressure loads.
- External Hopper Support - The front wall strength was inadequate to support the hopper due to the large number of tube bends. An external hopper support was constructed to handle the hopper weight.

The original equipment burner control system at WIPCO included the following components:

- Oil fired ignition system;
- Flame scanners;
- Manual register drives (4).

This system was installed in 1965 and is not representative of modern burner control systems. It was inadequate to control the DMBs and the tertiary air ports. A new control system was installed with electric drives on the registers and on the tertiary air ports.

4.2 Air Flow Rate Measurement and Control

The prototype burner test results presented in Section 2 showed that NO_x emissions were sensitive to burner zone stoichiometry. Thus it is desirable to measure and control burner zone stoichiometry during the WIPCO field evaluation. There is no independent system to measure and control burner zone stoichiometry. However, burner zone stoichiometry can be calculated from the air flow rate distribution among the burner passages. This section discusses the measurement and control of air flow rates through the passages of the burners installed at WIPCO. Each burner passage is equipped with an airflow rate measurement and control device. The design and calibration of these devices are discussed in the following subsection. Subsection 4.2.2 discusses the use of the calibration data to evaluate the burner operating point.

4.2.1 Design and Calibration of Air Flow Rate Measurement and Control Devices

The DMBs installed at WIPCO are supplied with combustion air from two sources. The coal nozzles are supplied with air (and coal) from the pulveri-

zers. The primary air flow rates to each pulverizer are measured and controlled with the existing boiler instrumentation. The other burner passages including the core, inner and outer secondaries for each burner as well as the tertiary air ports are supplied with preheated air from a common windbox. Each of the 22 passages is equipped with an air flow rate measurement and control system as shown schematically in Figure 4-7. Seven separate types of system are used. Each has a movable control element which varies the effective open area of a flow restriction. The pressure drop across the flow restriction is measured and the relationship between flowrate and pressure drop is calibrated for each position of the control element.

The air flow exiting each burner throat is supplied from the core air valve, inner register and outer register. A butterfly valve is used to control and measure the air flow rate to the core. The inner and outer registers are equipped with cylindrical perforated plates (air hoods) and concentric sliding sleeves (Foster Wheeler's patented method for measuring and controlling secondary air flow to a burner). The positions of the sliding sleeve set the effective open areas of the perforated plates and the pressure drops are measured across the entire assemblies (sleeves and perforated plates).

Four types of control devices are used on the tertiary air ports as shown schematically in Figure 4-8. This figure shows the windbox as an open area with registers, coal nozzles, trusses, and buckstays deleted for simplicity. The top, outboard and center ports are controlled by three sizes of cylindrical control valves. Each valve has two parts: a stationary inner cylinder with four perforated plates in the circumference and a rotating outer cylinder with slots matching the perforated plate locations. Rotating the outer cylinder changes the alignment between the slots and perforated plates and this varies the effective open area. The pressure drop is measured across both elements. The bottom four tertiary air ports are supplied with air from a separate plenum below the windbox. The airflow rate into the plenum is controlled by a sliding plate which varies the open area of a stationary perforated plate. The pressure drop is measured between the windbox and plenum.

The relationship between the air flow rate and the pressure drop across a control valve can be expressed as:

$$1. \quad Q = K \left(\frac{\Delta P}{T} \right)^{\frac{1}{2}}$$

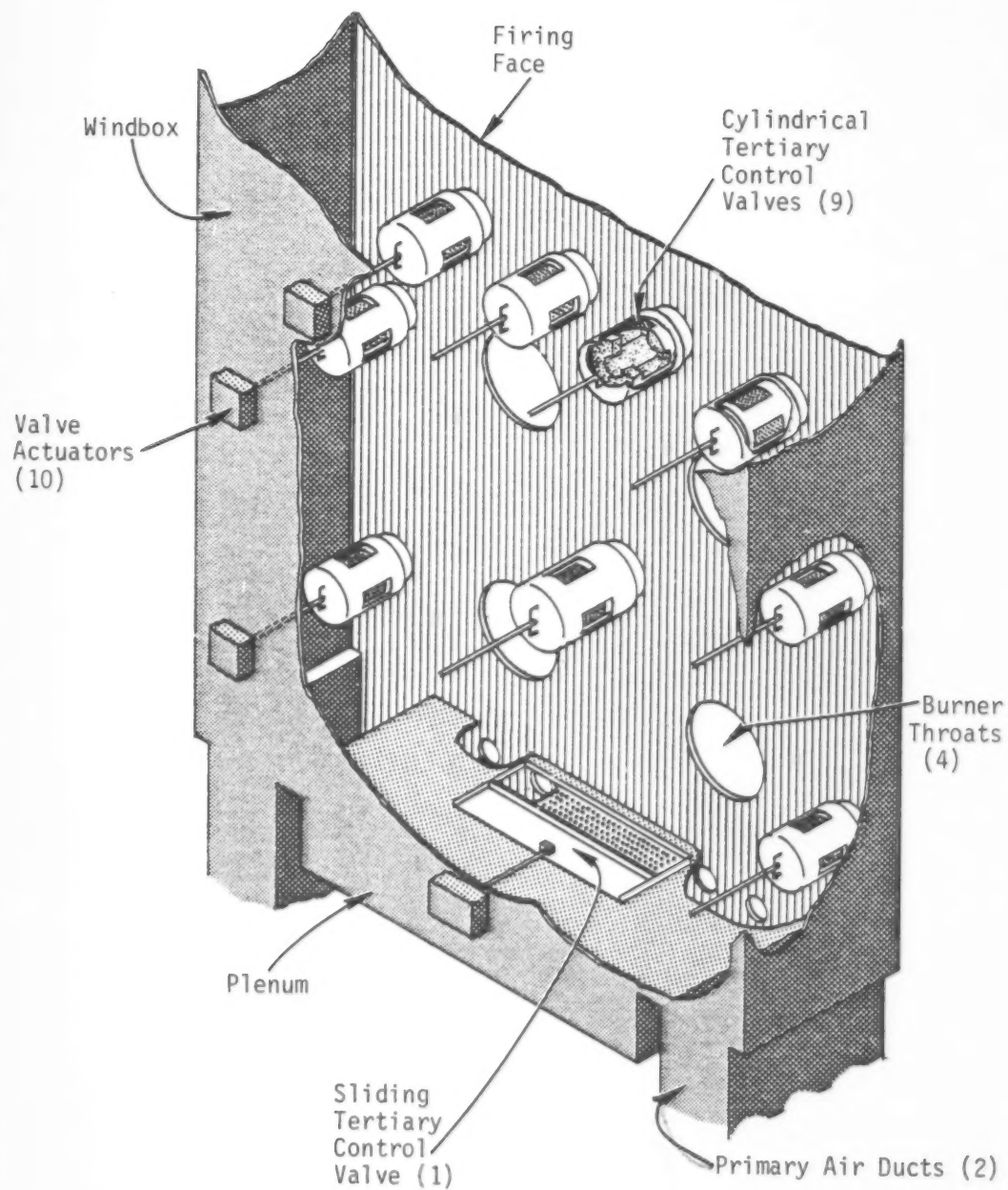


Figure 4-8. Tertiary air ports for WIPCO DMBs.

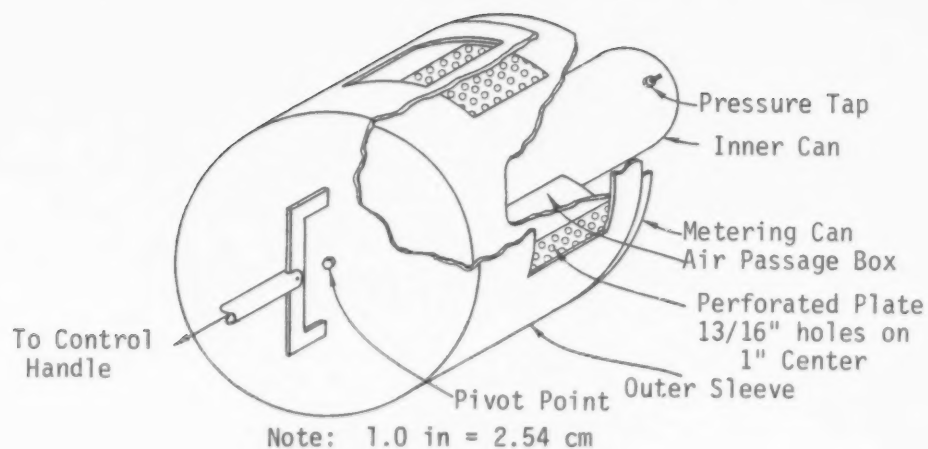
where:

- Q = mass flow rate through the tertiary port
- ΔP = pressure drop across the control valve
- T = absolute air temperature
- K = a calibration constant which may depend on Reynolds number, air flow pattern around pressure taps, effective open area of the control valve and units used for the other parameters.

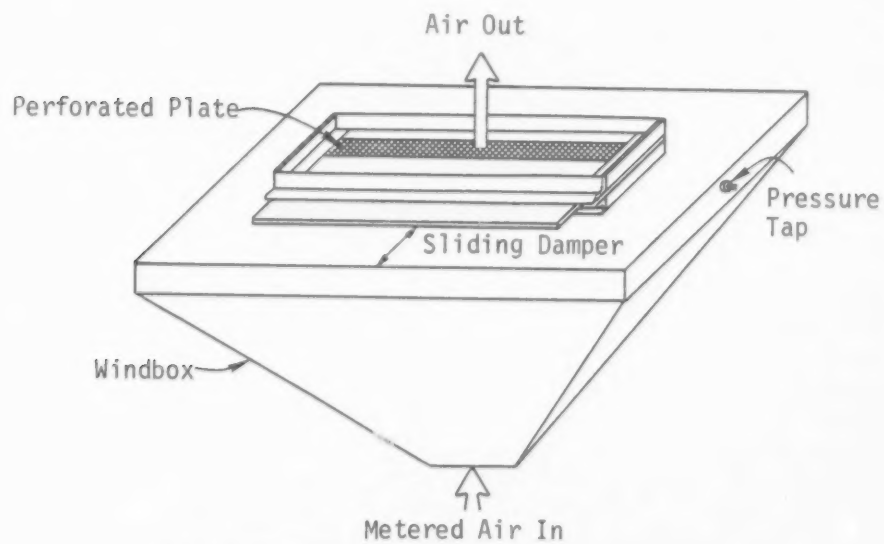
For the high Reynolds number flow conditions at which the devices typically operate, Reynolds number effects are small and usually can be neglected. The effects of air flow patterns in the vicinity of the pressure taps and open area must be evaluated through calibration.

The air flow rate measurement and control devices on the core, inner register and outer register were calibrated previously and the results were presented in the Second Annual Report. During the third year (ending November, 1981) the tertiary air port control systems were calibrated. Full-scale models of the four types of control assemblies were constructed and tested. Their construction is illustrated in Figure 4-9. The three sizes of cylindrical control valves were constructed to match the geometry of the field operating units. However, the materials were of lighter gauge, the pivot points were simpler, and the refractory was eliminated and replaced by inner cylinders connected to the metering cans by air passages formed by boxes. The tests were conducted by flowing air, metered by a calibrated venturi, through a cylindrical windbox in which each valve was installed. The angular position of the outer sleeve was measured with a protractor. The air flow rate, through the valve, was calibrated by measuring the pressure differential across the control valve with a manometer. The sliding damper assembly was calibrated similarly with metered air at several damper positions.

The calibration data for the outboard tertiary air port control valves are shown in Figure 4-10. The lines drawn through the data are regression analysis fits to equation 1. Rotating the sleeve 30° from full-open reduced the air flow rate to the minimum level. Additional rotation to 45° from full-open caused no change in the air flow rate. The regression correlations for each sleeve position are listed in Table 4-1. The design of the control valve



a) Cylindrical Tertiary Port Control Valve



b) Sliding Damper Assembly

Figure 4-9. Full scale calibration models of tertiary control devices to be used at demonstration boiler.

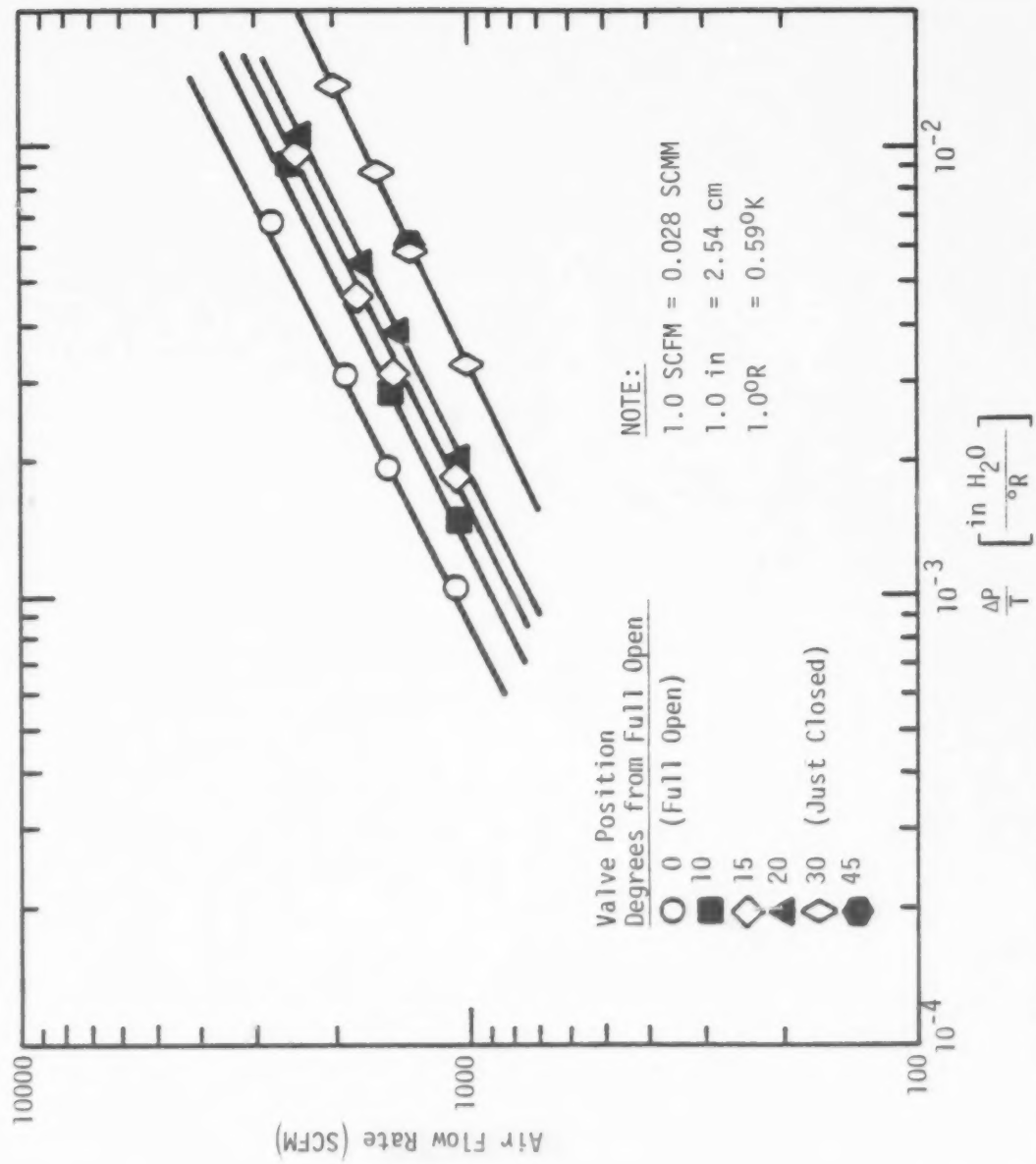


Figure 4-10. Outboard tertiary air port control valve calibration data.

TABLE 4-1. AIR FLOW RATE CORRELATION - OUTBOARD
TERTIARY AIR PORT CONTROL VALVES

Sleeve Position (deg. from Open)	Flow Rate Correlation	Standard Deviation (%)
0	$Q = 33783 (\Delta P/T)^{1/2}$	± 1.4
10	$Q = 27861 (\Delta P/T)^{1/2}$	± 1.3
15	$Q = 26074 (\Delta P/T)^{1/2}$	± 2.6
20	$Q = 23464 (\Delta P/T)^{1/2}$	± 0.86
30	$Q = 17840 (\Delta P/T)^{1/2}$	± 0.88
Combined Results		
$0^\circ \leq P_s \leq 30^\circ$	$Q = (33638 - 522 P_s)(\Delta P/T)^{1/2}$	± 1.4
$P_s > 30^\circ$	$Q = 17978 (\Delta P/T)^{1/2}$	

NOTE:

Q = [SCFM]
 ΔP = [in H₂O]
 T = [^oR]
 P_s = [Degrees from Open]

1.0 SCFM = 0.028 SCMM

1.0 in = 2.54 cm

1.0^oR = 0.59^oK

provides a linear relationship between valve position and effective open area. This can be seen in Figure 4-11 where the calibration constants are plotted against valve position. A linear regression analysis results in the overall correlation listed in Table 4-1. The flowrates predicted by this correlation based on the $\Delta P/T$ measurements and the measured flowrates are compared in Figure 4-12. The standard deviation is 1.4 percent.

Similar calibrations were conducted for the other two cylindrical control valves. The data and correlations are shown in Figures 4-13 and 4-14 and Tables 4-2 and 4-3.

The calibration data for the lower tertiary air port control valve is shown in Figure 4-15 and the correlations with valve position are shown in Table 4-4. For this valve, the relationship between the calibration coefficient and valve position is non-linear. Figure 4-16 is a log-log plot of calibration constant versus valve position. The line shown through the data is a regression analysis fit using the relationship $K = A P_D^m$ where A and m are constants. Table 4-4 lists this overall correlation which fits the data with a standard deviation of 8.8 percent.

The calibration correlation for the tertiary air port control devices as well as the core and register control devices are summarized in Table 4-5. There are two correlations for each control device. One relates the air flow rate through the burner passage to the indicated pressure drop and control device setting. This type of correlation will be used to calculate the air flow rate through each burner passage during the WIPCO field tests. The other correlation is the relationship between air flow rates and windbox to furnace pressure differential for various burner settings. This correlation will be used to calculate the air flow rates and windbox pressure which would be produced by specific burner settings.

4.2.2 Evaluation of Burner Operating Point

The calculation of primary, burner zone and overall stoichiometries is illustrated in Figure 4-17. The overall stoichiometry is calculated from the exhaust gas composition and coal composition. If measurements of carbon in the bottom ash and fly ash as well as CO emissions confirm high combustion efficiency, overall stoichiometry will be calculated assuming complete combustion.

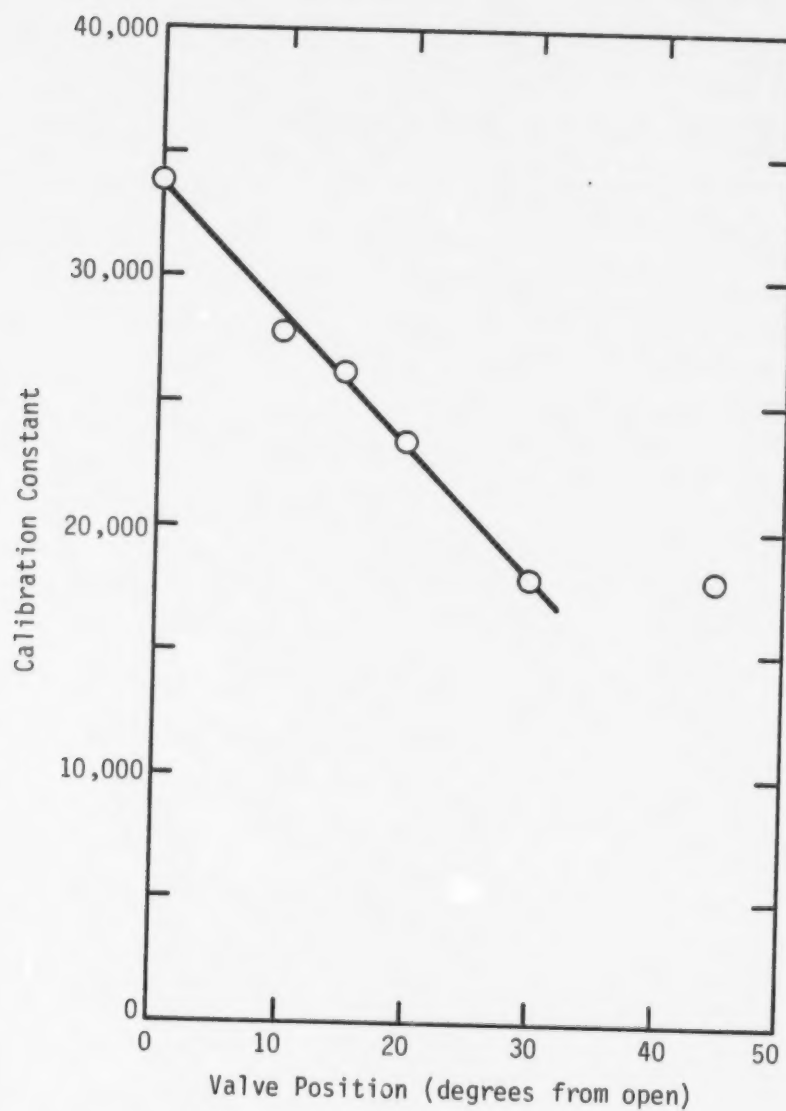


Figure 4-11. Calibration constant for outboard tertiary air port control valve.

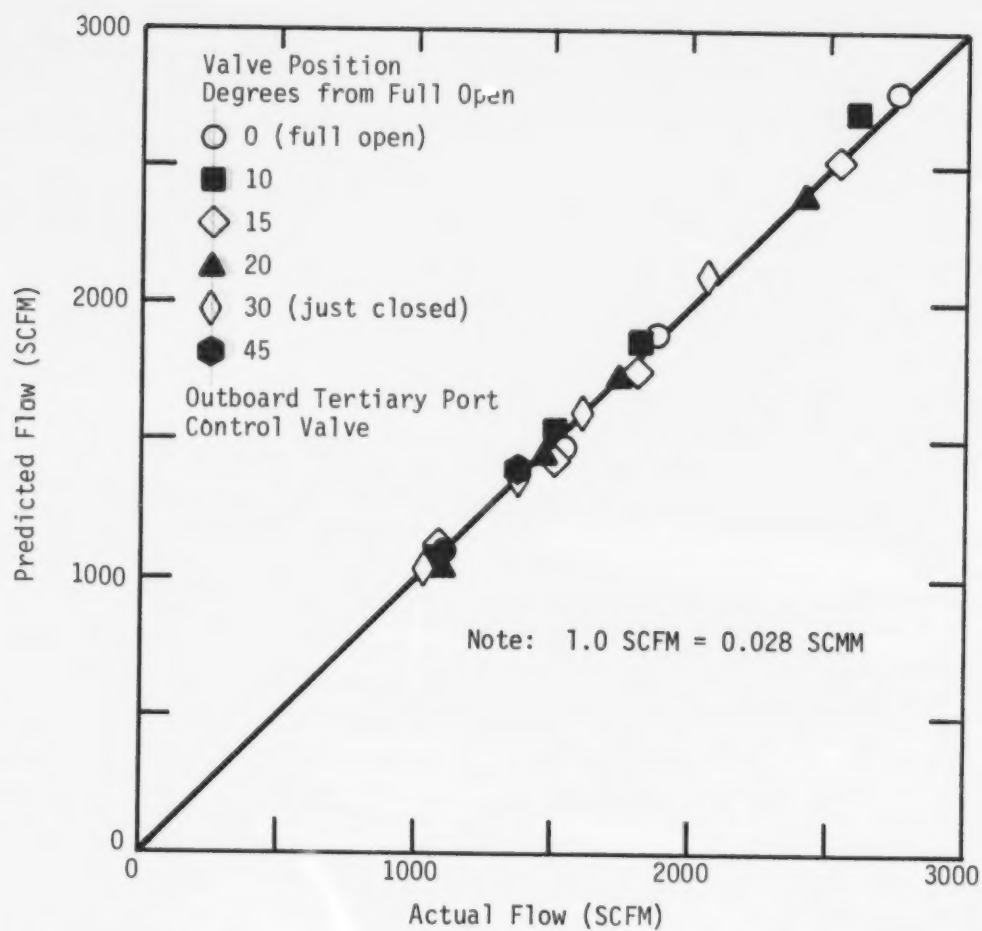


Figure 4-12. Comparison of flowrate predicted by correlation and measured flowrate.

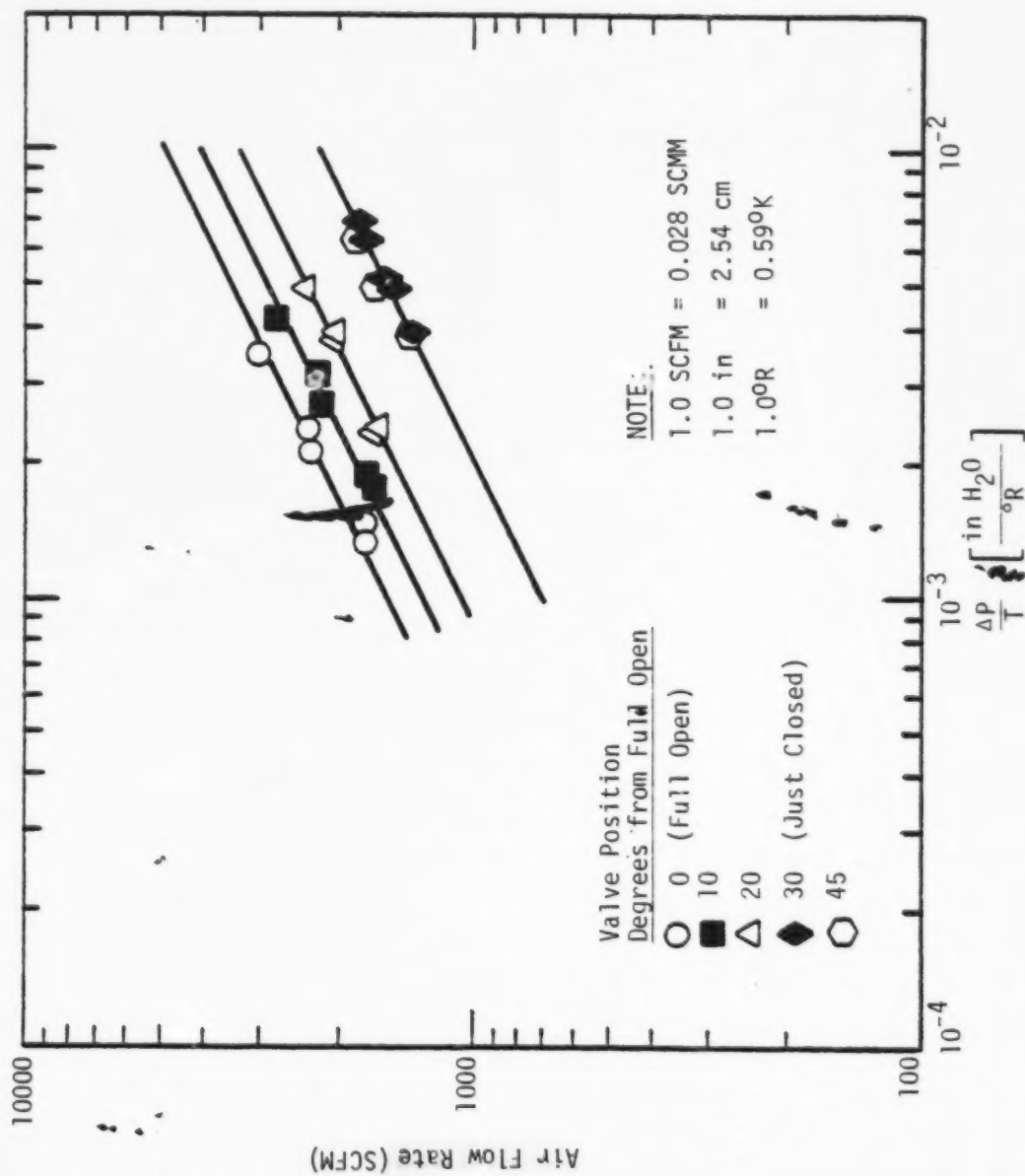


Figure 4-13. Upper tertiary air port control valve calibration data.

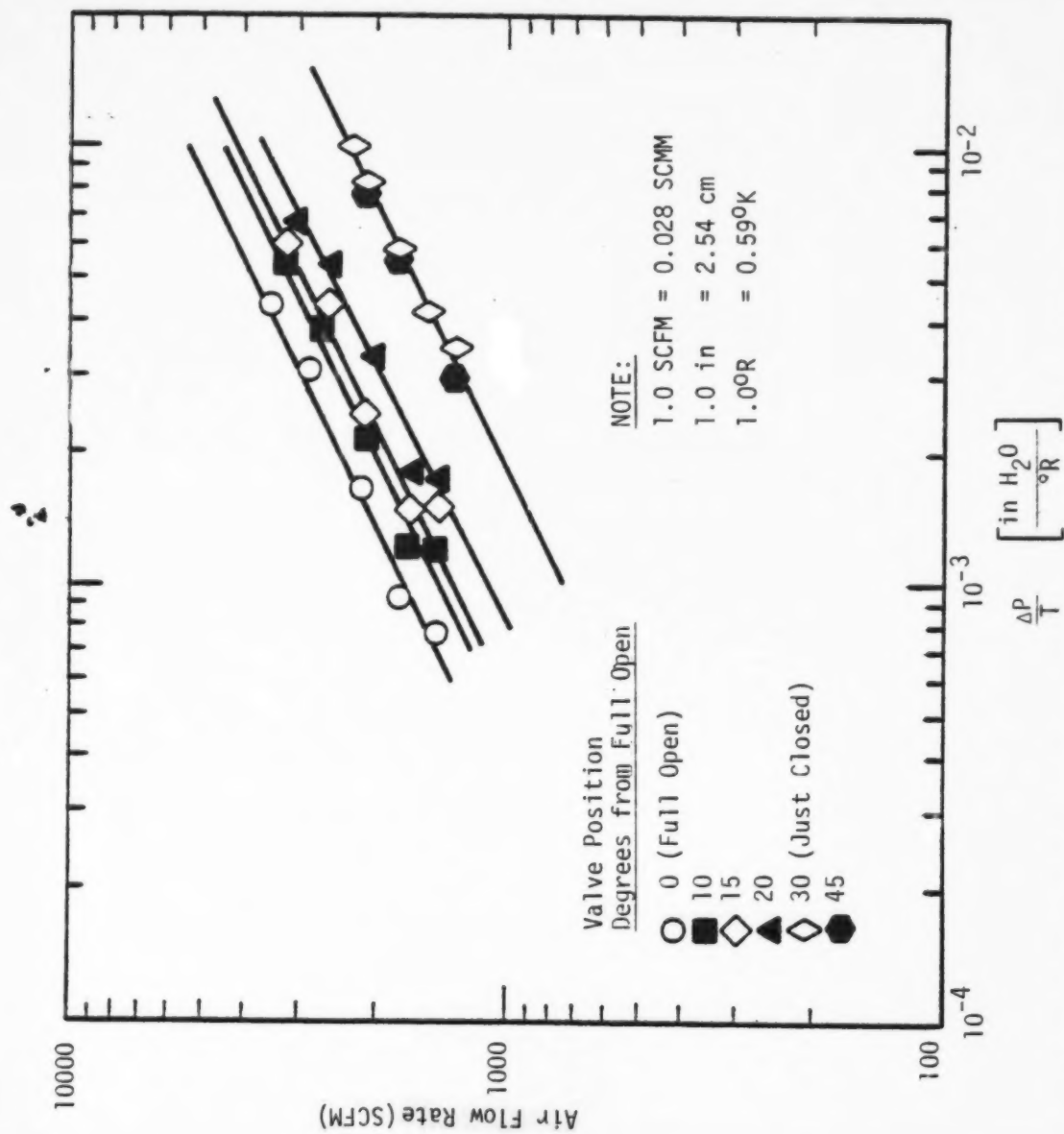


Figure 4-14. Center tertiary air port control valve calibration data.

TABLE 4-2. AIR FLOW RATE CORRELATION - UPPER TERTIARY AIR
PORT CONTROL VALVES

Sleeve Position (Deg. from Open)	Flow Rate Correlation	Standard Deviation (%)
0	$Q = 48775 (\Delta P/T)^{1/2}$	± 4.2
10	$Q = 41343 (\Delta P/T)^{1/2}$	± 3.3
20	$Q = 34222 (\Delta P/T)^{1/2}$	± 2.9
30	$Q = 22243 (\Delta P/T)^{1/2}$	± 1.7
45	$Q = 23378 (\Delta P/T)^{1/2}$	± 3.3
Combined Results		
$0^\circ \leq P_s \leq 30^\circ$	$Q = (49653 - 867 P_s) (\Delta P/T)^{1/2}$	± 4.0
$P_s > 30^\circ$	$Q = 23643 (\Delta P/T)^{1/2}$	

NOTE:

Q = [SCFM]

ΔP = [in H_2O]

T = [$^\circ R$]

P_s = [Degrees from Open]

1.0 SCFM = 0.028 SCMM

1.0 in = 2.54 cm

1.0 $^\circ R$ = 0.59 $^\circ K$

TABLE 4-3. AIR FLOW RATE CORRELATION - CENTER TERTIARY
AIR PORT CONTROL VALVE

Sleeve Position (Deg. from Open)	Flow Rate Correlation	Standard Deviation (%)
0	$Q = 53939 (\Delta P/T)^{1/2}$	± 3.8
10	$Q = 45478 (\Delta P/T)^{1/2}$	± 5.8
15	$Q = 42306 (\Delta P/T)^{1/2}$	± 4.5
20	$Q = 36283 (\Delta P/T)^{1/2}$	± 5.4
30	$Q = 23185 (\Delta P/T)^{1/2}$	± 1.3
45	$Q = 24900 (\Delta P/T)^{1/2}$	± 1.1
Combined Results		
$0^\circ \leq P_s \leq 30^\circ$	$Q = (55457 - 1015 P_s)(\Delta P/T)^{1/2}$	± 4.2
$P_s > 30^\circ$	$Q = 25007 (\Delta P/T)^{1/2}$	

NOTE:

Q = [SCFM]

ΔP = [in H₂O]

T = [°R]

P_s = [Degrees from Open]

1.0 SCFM = 0.028 SCMM

1.0 in = 2.54 cm

1.0°R = 0.59°K

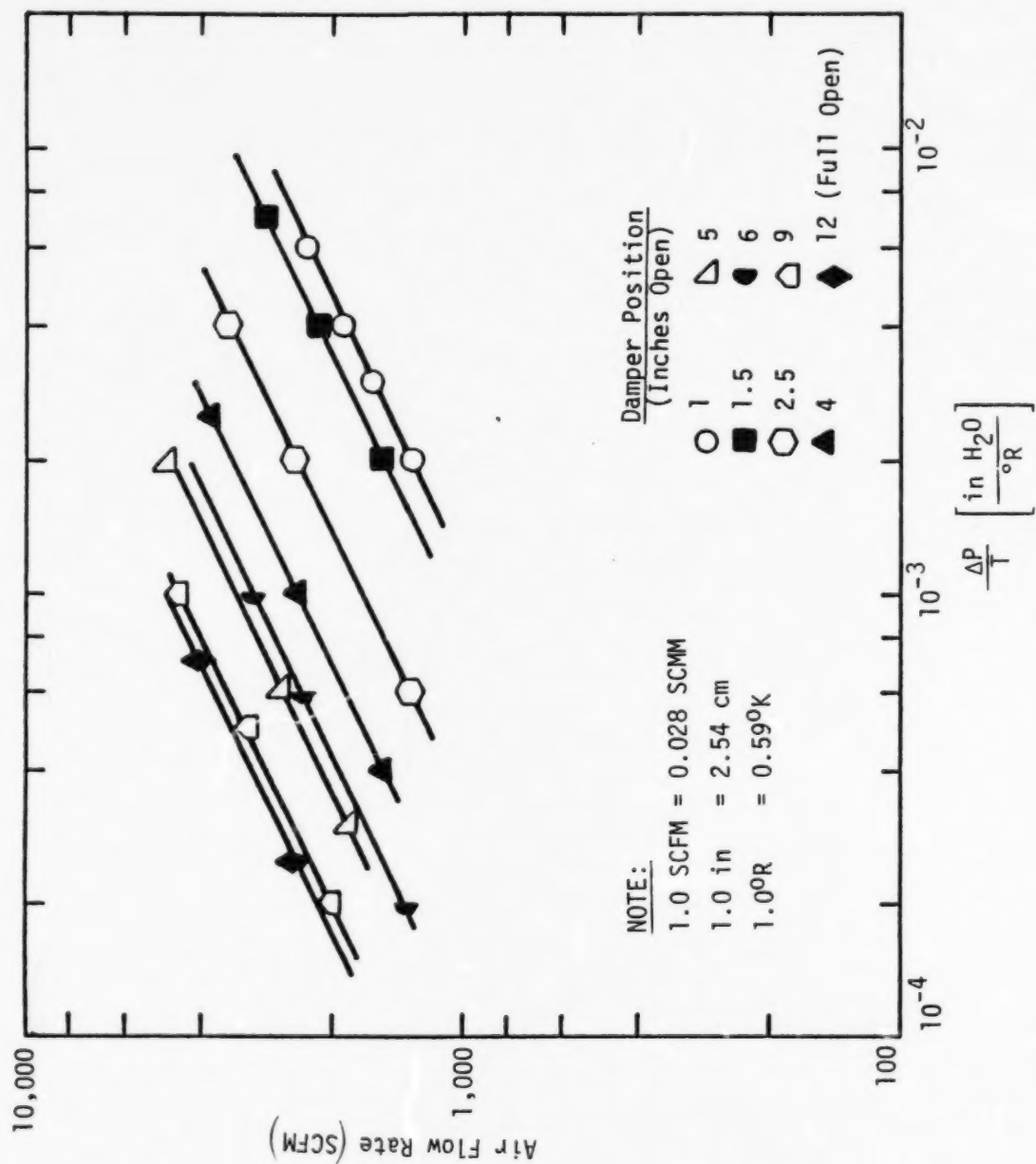


Figure 4-15. Lower tertiary air port control valve calibration data.

TABLE 4-4. AIR FLOW RATE CORRELATION - LOWER TERTIARY
AIR PORT CONTROL VALVE

Damper Position (Inches Open)	Flow Rate Correlation	Standard Deviation (%)
1	$Q = 29635 (\Delta P/T)^{1/2}$	± 11.6
1.5	$Q = 34285 (\Delta P/T)^{1/2}$	± 12.4
2.5	$Q = 54793 (\Delta P/T)^{1/2}$	± 1.9
4	$Q = 76630 (\Delta P/T)^{1/2}$	± 4.4
5	$Q = 105051 (\Delta P/T)^{1/2}$	± 12.5
6	$Q = 97814 (\Delta P/T)^{1/2}$	± 7.8
9	$Q = 142824 (\Delta P/T)^{1/2}$	± 5.1
12	$Q = 152862 (\Delta P/T)^{1/2}$	± 6.5
Combined Results		
$0 \leq P_d \leq 12"$	$Q = 28501 P_d^{0.7131} (\Delta P/T)^{1/2}$	± 8.8

NOTE:

Q = [SCFM]

ΔP = [in H₂O]

T = [^oR]

P_d = [Inches Open]

1.0 SCFM = 0.028 SCMM

1.0 in = 2.54 cm

1.0^oR = 0.59^oK

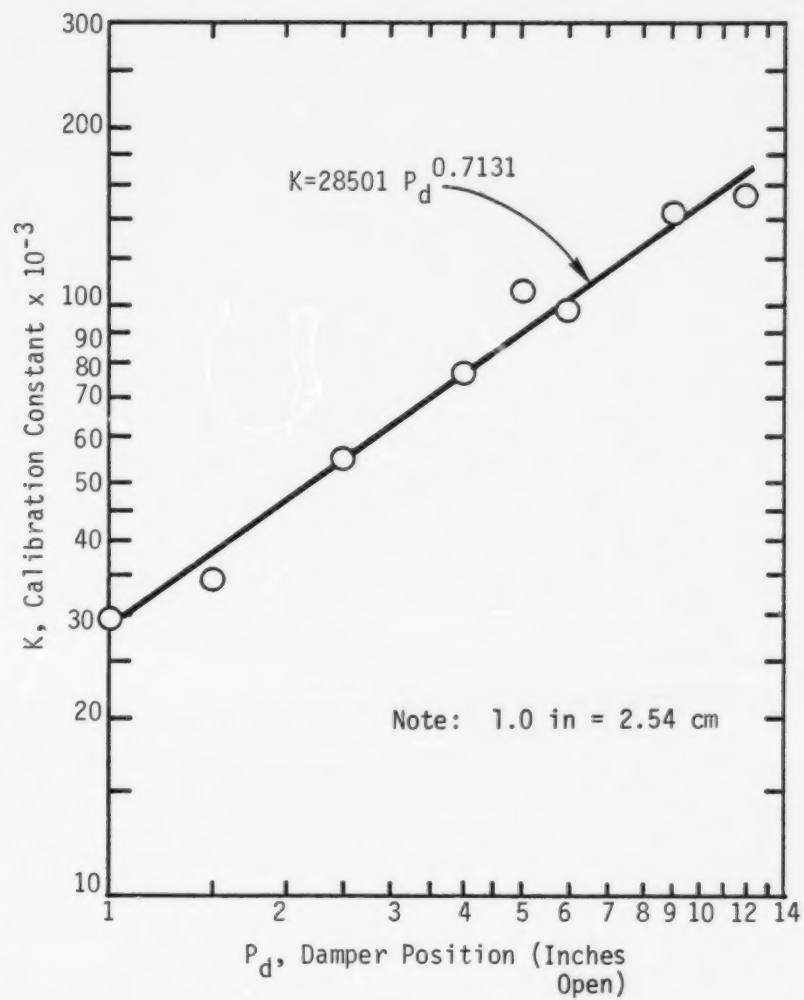


Figure 4-16. Calibration constant for lower tertiary port control valve.

TABLE 4-5. CALIBRATION SUMMARY

Burner Passage	Flowrate Correlation i^{**} $Q = (K)(\Delta P_i/T)^{1/2}$	Windbox to Furnace Pressure Drop i^{**} $Q = (K)(\Delta P_{wb}/T)^{1/2}$	Control System Variables
Core	18500 - 182 P_V	18500 - 182 P_V	P_V = Degrees from Full Open
Outer Secondary*	96000 + 1430 P_S	202000 - 1970 P_r	P_r = Degrees from Full Open
Inner Secondary*	509 + 751 P_S	$(0.64 + 0.0036 P_S) \times (93200 - 515 P_r)$	P_r = Degrees from Full Open P_S = Percent Open
Upper Tertiary	49653 - 867 P_S	49653 - 867 P_S	P_S = Degrees from Full Open (0-30)
Outboard Tertiary	33638 - 522 P_S	33638 - 522 P_S	P_S = Degrees from Full Open (0-30)
Center Tertiary	55457 - 1015 P_S	55457 - 1015 P_S	P_S = Degrees from Full Open (0-30)
Lower Tertiary	$28501 P_d^{0.7131}$	$\left\{ \frac{(28501 P_d^{0.7131})^2}{1 + \left(\frac{7.99525 \times 10^{-7}}{T} \right) (28501 P_d^{0.7131})^2} \right\}^{1/2}$	P_d = Inches from Closed (0-12)

NOTE:

Q = SCFM
 ΔP_{wb} = in H₂O
 ΔP_i = in H₂O
 T = °R

1.0 SCFM = 0.028 SCMM
 1.0 in = 2.54 cm
 1.0°R = 0.590K

* Windbox pressure data are based on Prototype 1 calibrations. The changes in exit geometry in Prototype 2 may affect these results.

** K = Relationships for coefficient.

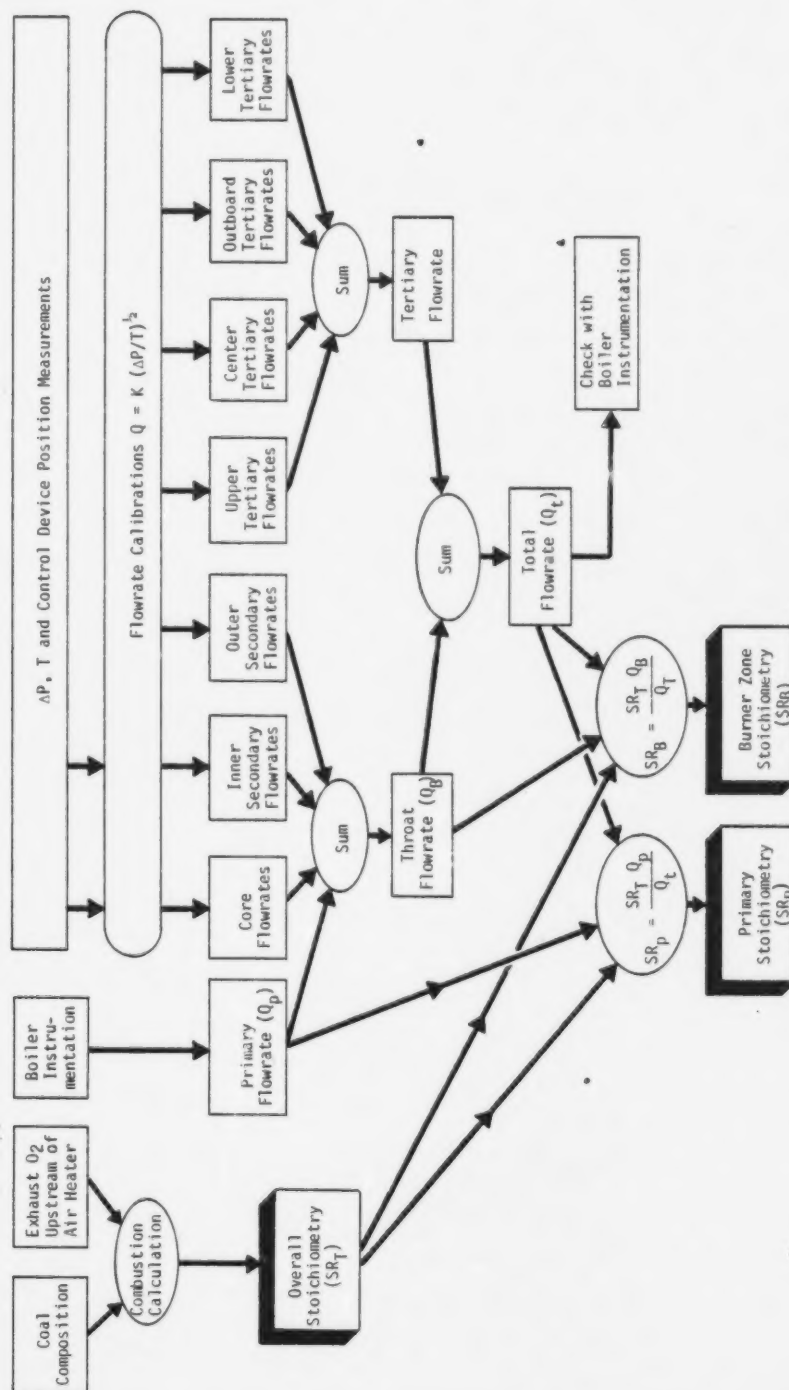


Figure 4-17. Calculation of stoichiometries.

The primary and burner zone stoichiometries are calculated based on air flow rate measurement. The primary air flow rate is measured with calibrated venturis on the air supply to each pulverizer. The air flow rates in the other passages are calculated from the windbox temperatures, the indicated pressure drop and position of the 22 control devices, and the correlations discussed in the previous section. The primary, core, inner secondary and outer secondary flowrates are summed to calculate the total air flowrate through the burner throats. The total air flowrate through the tertiaries is calculated in a similar manner. Primary and burner zone stoichiometries are calculated from the overall stoichiometry and the ratio of air flowrate through the primary and burner throat to the total air flow respectively. A computer program is being developed to allow rapid evaluation of stoichiometries in the field.

The air flow rate calibrations can be used to determine the burner operating point for specific burner settings. It is expected that the windbox to furnace pressure differential will be approximately constant throughout the windbox. If this is the case, the burner operating point can be calculated directly by a simple graphical technique. Figure 4-18 shows the windbox to furnace pressure differential as a function of burner zone stoichiometry for full load operation. The primary and overall stoichiometries are 20 and 120% TA, respectively. Two families of curves are plotted: one for the burner throats and the other for the tertiary air ports. The range for the burner throats is achieved by adjusting the sleeves, registers and control valves. For fixed positions, a single line results. The range for the tertiary air ports represents the extreme positions for all control devices: all full open or all full closed. The intersections of the curves are the burner operating points for specific settings. The heavy lines are the ranges of adjustment provided by opening/closing the tertiary air ports, about 20% TA. Note that a specific burner zone stoichiometry can be produced over a wide range of windbox to furnace pressure differentials by adjusting the sleeves around the registers. At WIPCO, the burner will be adjusted to provide the lowest windbox to furnace pressure differential commensurate with other constraints such as air supply to the pulverizers, resonances, etc.

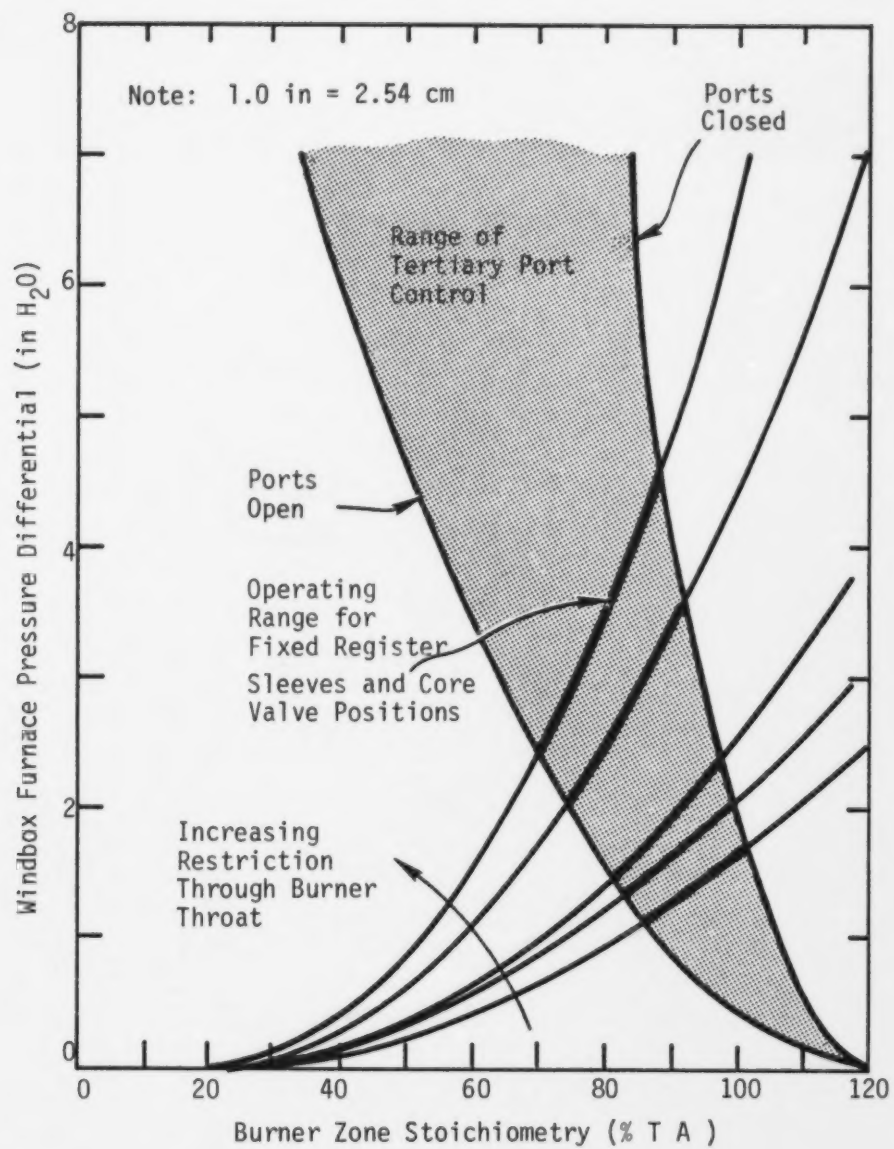


Figure 4-18. Field operable burner performance at full load and 120 % T A

5.0 CONCLUSIONS AND FUTURE EFFORTS

5.1 Conclusions

Based on the work conducted during this third year of the program, the following conclusions have been reached:

1. Prototype Burner Tests

The prototype burner tests in the LWS demonstrated that the DMB meets all requirements of the host boiler. NO_x emissions were 95 ng/J ($0.22 \text{ lb}/10^6 \text{ Btu}$). This is close to the program goal of 87 ng/J ($0.2 \text{ lb}/10^6 \text{ Btu}$).

2. Boiler Baseline Evaluation

The host boiler performance was found to be typical of pre-NSPS pulverized coal-fired boilers. NO_x emissions during a 30-day test averaged 433 ng/J ($0.95 \text{ lb}/10^6 \text{ Btu}$). No significant NO_x reduction could be achieved by low excess firing or burner adjustments.

3. DMB Field Evaluation

The DMBs were installed in the host boiler in the spring of 1981. To accommodate the structural constraints imposed by the existing windbox/furnace, it was necessary to modify the tertiary air port array from the configuration tested in the LWS. The burners are now operating satisfactorily with the tertiary air ports closed.

5.2 Future Efforts

Future efforts will be focused on two principal objectives:

- Field evaluation of the DMBs installed in the WIPCO host boiler;
- Development and research furnace tests of a prototype DMB based on the DMB design criteria.

The DMBs have been installed in the WIPCO furnace and are now operating unstaged. At a future outage, tube wall thickness measurements will be made throughout the furnace to establish a baseline for corrosion rate measurements. Following the outage, the DMBs will be tested over a range of operating conditions and burner settings to establish an optimum balance of flame

stability, efficiency and emissions. The initial operating point will be the optimum settings established during the LWS tests of Prototype 2. Due to the difference between the LWS and WIPCO furnaces, it is expected that some adjustments of burner settings may be required. Burner performance, boiler performance and emissions will be measured over the full range of operating parameters and burner settings as specified in the measurements protocol. Once the optimum operating point is established the boiler operators will be trained to operate the unit. Following the training program, the operators will run the unit over the normal duty cycle while burner performance, boiler performance and emissions are monitored. At the conclusion of the testing period, the unit will be restored as required by the boiler owner. Also, furnace tubewall thickness measurements will be made to evaluate the rate of corrosion.

During the LWS tests of Prototype 1, the flame stability at the burner design point was found to be unacceptable. Due to a time constraint on the burner installation at WIPCO, a decision was made to alter the burner exit geometry to the Foster Wheeler Controller Flow burner exit geometry since burners with this geometry have been demonstrated to have adequate flame stability under reducing conditions with overfire air ports. However, this geometry is not necessarily optimum for DMB operation. Consequently, a second series of prototype burner tests will be conducted to optimize performance under DMB conditions. This will involve making iterative modifications to the nozzle and throat geometry and evaluation of flame stability, efficiency and emissions in the LWS.

6.0 ABBREVIATIONS

CO	Carbon monoxide
CO ₂	Carbon dioxide
DMB	Distributed mixing burner
HCN	Hydrogen cyanide
LOAD	Burner firing rate, or boiler steam or electrical power generating rate
LWS	Large watertube boiler simulator, a burner test facility
MT	Medium tunnel, a burner test facility
NH ₃	Ammonia
NO _x	Nitrogen oxides including nitric oxide (NO) and nitrogen dioxide (NO ₂)
O ₂	Oxygen
Prototype 1	The prototype DMB initially constructed in this program. The burner design is based on integrating the EPA distributed mixing burner design criteria with Foster Wheeler burner components.
Prototype 2	A modified version of Prototype 1 where the burner nozzle and exit geometry were changed to match the specifications of the Foster Wheeler Controlled Flow Burner.
Q/A	Furnace heat release per effective cooled surface area.
SO ₂	Sulfur dioxide
SO ₃	Sulfur trioxide
SR _B	Burner zone stoichiometry
SR _T	Overall stoichiometry
% TA	Percent theoretical air
WIPCO	Western Illinois Power Cooperative

APPENDIX

The Medium Tunnel Test Facility (MT) is an axisymmetric furnace with a maximum firing capacity of 80×10^6 Btu/hr. The major systems comprising the facility include:

- Furnace
- Cooling
- Fuel Supply
- Air Supply
- Exhaust
- Instrumentation

The overall layout of the facility is shown in Figure A-1.

A.1 Furnace

The MT Furnace is a 4.3 m (14.0 ft) diameter cylinder, 6.1 m (20 ft) long. The cylinder axis is horizontal with test burners mounted in one end of the furnace. The exhaust exits through a 1.5 m (5 ft) diameter duct in the center of the target wall. Figure A-2 shows the general configuration of the MT, and Table A-1 lists its design parameters and dimensions. To provide a thermal environment similar to large industrial and utility boilers, the MT is partially lined with insulating refractory. The target wall is fully insulated and the cylinder is 40 percent insulated in axial strips. Additional insulation can be inserted between the refractory strips to decrease the heat removal.

A.2 Cooling

The entire exterior surface of the MT furnace and exhaust system is continuously sprayed with water to absorb the heat of combustion. The furnace is slightly elevated over a shallow sump so that the fraction of water which is not evaporated can be recycled. Based on previous experience with similar facilities, the outside furnace wall temperature will be in the range of 121 to 149°C (250 to 300°F). Inside the furnace, the flame will be exposed to an average wall temperature comparable to field operating boilers (i.e., a balance between the insulated walls at about 149°C (300°F) and the insulated walls at

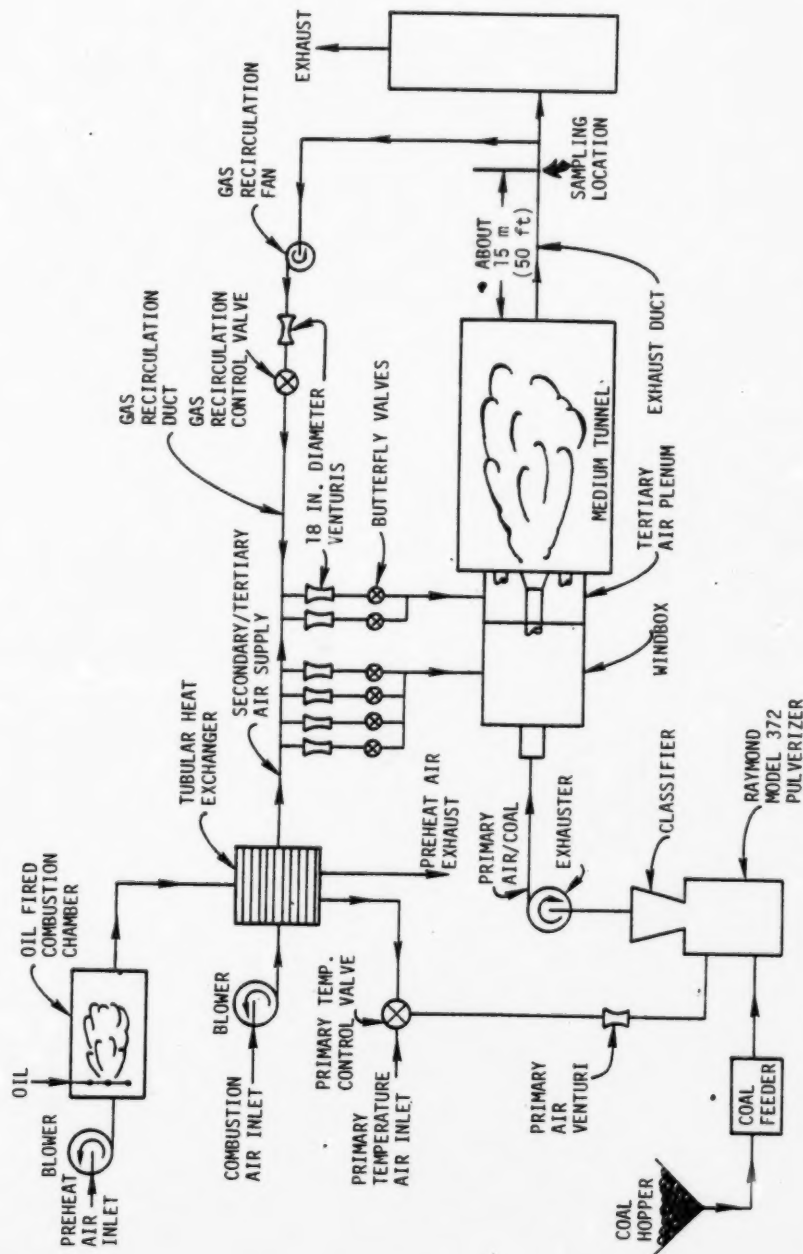


Figure A-1. Medium Tunnel Facility flowchart.

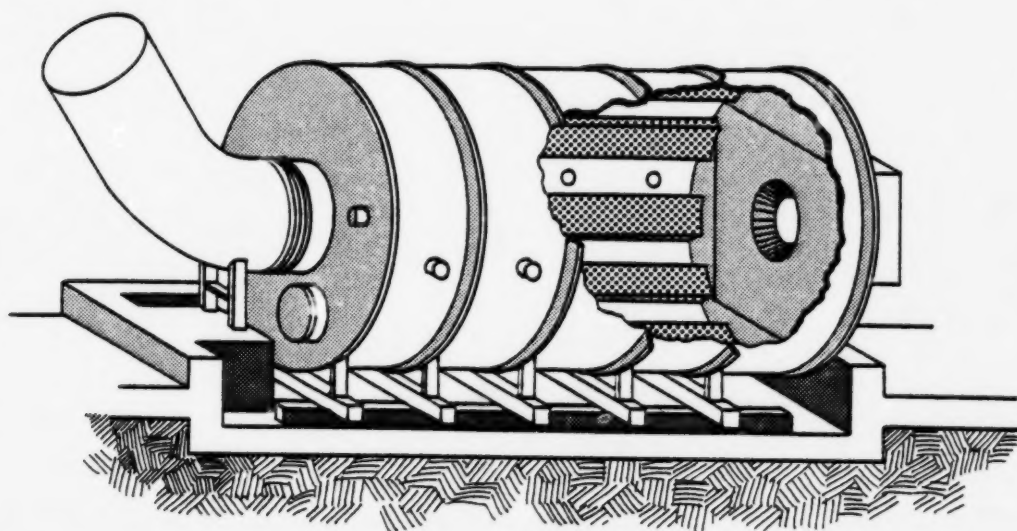


Figure A-2. Cutaway view of Medium Tunnel Test Furnace (MT).

TABLE A-1. EER MEDIUM TUNNEL SPECIFICATIONS

Parameter	EER Medium Tunnel
Capacity (10^6 Btu/hr) [MW]	80 [23.4]
Shape	Horizontal Cylinder
Firing Configuration	Cylinder End
Exhaust	Opposite End
Insulation	46% of Surface Covered
Heat Removal	External Spray Cooling
Diameter (ft) [m]	14 [4.3]
Length (ft) [m]	20 [6.1]
Volume (ft^3) [m^3]	3079 [87.2]
Total Surface Area (ft^2) [m^2]	1188 [110]
Cooled Surface Area (ft^2) [m^2]	644 [59.8]
Heat Release/Cooled Surface Area (Btu/hr- ft^2) [W/m^2]	124×10^3 [3.91×10^5]
Heat Release/Volume (Btu/hr- ft^3) [W/m^3]	26.0×10^3 [2.69×10^5]

* At capacity

about 649°C [1200°F]).

A.3 Fuel Supply

The MT is equipped to fire either distillate oil or coal. However, other equipment can be provided to fire virtually any fuel. Distillate oil is supplied from underground tanks with pumping capacity sufficient to supply an 23.4 MW (80×10^6 Btu/hr) burner. Steam and air are available up to 689 kPa (100 psig) for atomization. Two Raymond coal pulverizers are available with capacities of approximately 23.4 and 44 MW ($80 \times 150 \times 10^6$ Btu/hr). These mills are equipped with cyclone classifiers and exhausters. Coal is delivered to the mills through a precision weight belt feeder which provides direct measurement and control of coal firing rate. During testing, the firing rate can also be back-calculated from the measurement of air flow rate into the furnace and the residence oxygen in the exhaust.

A.4 Air Supply

Combustion air is supplied by a forced-draft blower through a tubular heat exchanger and into a manifold. The combustion air flow rate is measured and controlled by multiple venturis and dampers. For burners equipped with a common windbox, several venturis can be connected in parallel as shown in Figure A-1. The use of multiple venturis allows accurate flow rate measurement over a wide flow rate range. The other side of the heat exchanger is supplied with hot exhaust from a separate oil-fired combustion chamber. This allows the combustion air preheat temperature to be controlled independently of the performance of the burner firing in the research furnace.

A.5 Exhaust

The MT furnace exhaust gases exit at about 1093°C (2000°F) and pass through an externally spray-cooled duct to a water quench tower. The furnace exhaust system was designed to permit a wide range of emission measurements. The sampling location is near the end of a long straight duct meeting EPA specifications for the minimum number of sampling points. Since there is no convective section, the temperature at the sampling point is about 538°C (1000°F). Downstream of the sampling location, the exhaust passes into a calcium carbonate scrubber which controls SO_x and particulate emissions. This system meets all applicable air pollution control regulations.

A.6 Instrumentation

The sample train for the continuous gas analyzers is shown in Figure A-3. All materials in contact with the sample are glass, 316 stainless steel or Teflon. These materials are non-reactive with NO at low temperatures. The stainless steel sampling probes are water cooled, and small cyclones adjacent to the probe remove particulate matter and condensed water. The sample is then transported to the control room through a Teflon line where it is filtered and dried. The sample pump is Teflon lined and the sample flow rate is maintained at several times the instruments' requirements to minimize response time. Excess sample flow is bypassed to a vent. Commercial gas analyzers are used for measurements of O₂, CO₂, CO, NO/NO_x, and SO₂ and are listed in Table A-2. The accuracy of each instrument is maintained by frequent calibration with zero and certified calibration gases.

The signals from the gas analyzers, venturis, weight belt, thermocouples and other instruments are interfaced with a computerized on-line data reduction system and data is printed out in convenient engineering units. This assists in the data analysis and allows test conditions to be established rapidly and accurately.

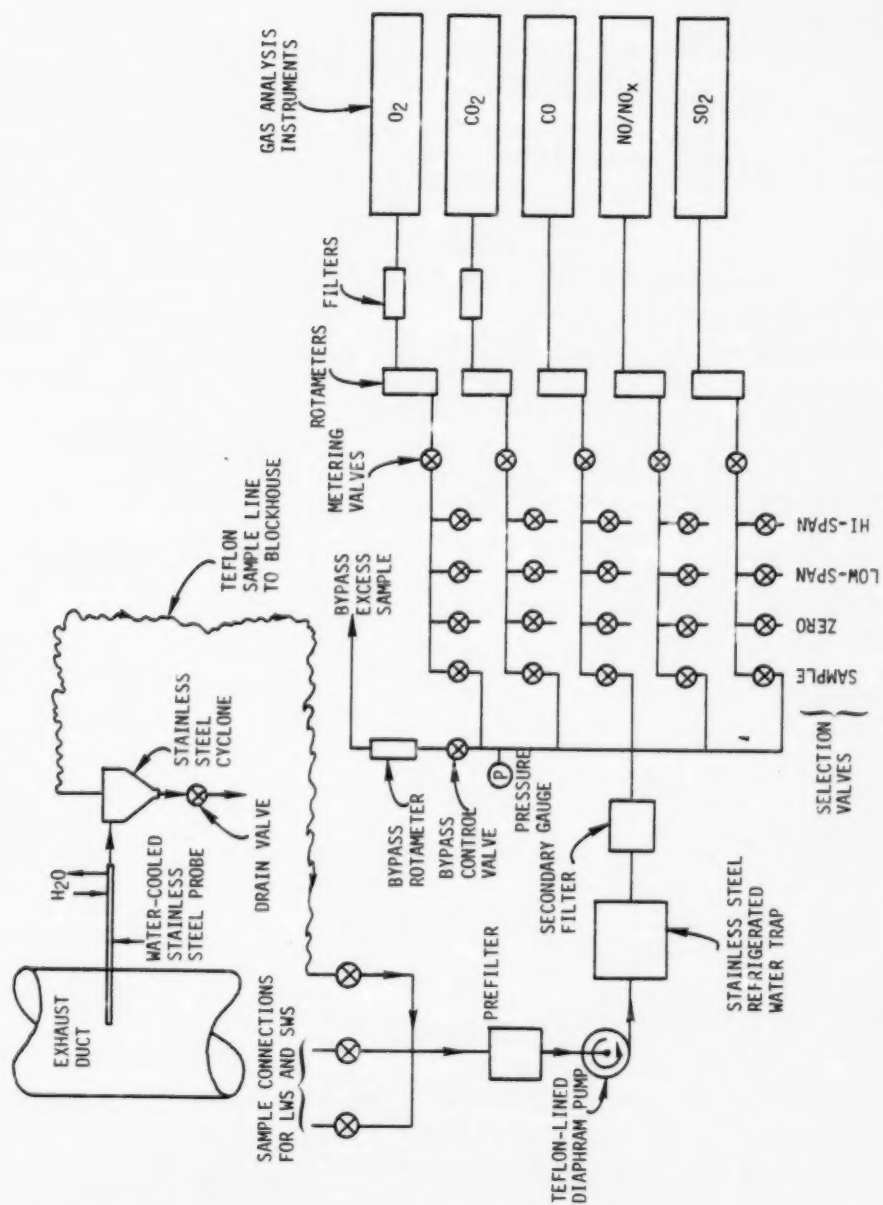


Figure A-3. Sample train schematic.

TABLE A-2. MT INSTRUMENTATION AND MEASUREMENTS

Parameter	Method	Record	Parameter	Method	Record
Burner settings	Manual	Manual	Flame characteristics	Manual and color video	Manual
Air flow rates	Calibrated venturis				
Temperatures	Thermocouple	Computer		Taylor, Paramagnetic Anarad, NDIR Anarad, NDIR	Computer and Strip Chart
Coal flow rates	Weight belt feeder and back-calculate from air flow rates and excess O ₂	Computer	O_2 CO CO_2 NO_x	Beckman, Chemiluminescent	
Coal fineness	ASME Sieve method	Manual	SO_2	TECO, Pulsed Fluorescent; and DuPont, Ultra-violet	
Coal Composition	Ultimate				
Stoichiometry	Calculate	Manual Computer	Particulate Mass Size distribution Composition Burner Pressure	High-Volume filter Andersen, Cascade impactor Ultimate Analysis Magnahelec	Manual Manual Manual Manual